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TECHNICAL NOTE

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ON THE EFFECT OF HEAT ADDITION IN THE EMPIRICAL CORRELATION OF VOID FRACTIONS FOR STEAM-WATER FLOW

By Uwe H. von Glahn and Richard P. Polcyn

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

An empirical equation is presented that closely approximates experimentally measured void fractions in steam-water flow with heat addition. Correlation of void fractions with heat addition is achieved through the use of steam quality, the ratio of the density of the fluid phases, a heat-addition parameter, and a fluid-property parameter. Void fractions without heat addition are also correlated by the proposed empirical equation. Correlation of data is achieved over a range of fluid pressures from 1 to 135 atmospheres and steam qualities from 0 to 1.0.

INTRODUCTION

For consideration of two-phase-flow pressure-drop and heat-transfer problems associated with net vapor generation during nucleate boiling and in order to achieve a competent evaluation of the performance characteristics for a boiling system, it is necessary to predict the vapor void fraction accurately. This is especially true for boiling-liquid reactors in which the operation and performance of the nuclear aspects of the reactor are interrelated to the two-phase flow characteristics in the system (ref. 1). For such systems, the effect of heat addition on the void fraction generated in the boiler or reactor tubes must be considered.

Void fraction in two-phase flow is generally defined as the volume ratio of vapor to total fluid, whereas the fluid quality is defined as the mass ratio of vapor to total fluid. The void fraction cannot be calculated directly from the relation of the ratio of vapor to liquid density and from the fluid quality because of the unknown velocity slip ratio (ref. 2), the complexity of the boiling process in a flowing system, and other effects (ref. 3). Consequently, the evaluation of void fractions is generally empirical. Recently, however, considerable progress has been made in postulating analytical models for the determination of void fractions in references 3 and 4. These references do not, however, consider the effect of heat addition on void fraction.

In reference 2 an empirical equation is described that approximates many of the experimentally measured void fractions for steam-water flow. The equation includes terms of steam quality and the ratio of the density of the fluid phases. No attempt is made in reference 2 to include the effect of heat addition on void fraction.

In the present study, conducted at the NASA Lewis Research Center, the empirical equation of reference 2 is modified to include the effect of heat addition on void fraction. This modified equation also represents void fractions for one-component two-phase flow without heat addition. Correlation of void fractions is herein achieved for conditions of net vapor generation through the use of a heat-addition parameter, which considers both heating rate and flow rate, and a fluid-property parameter. Correlation of steam-water data is achieved for a range of fluid pressures from 1 to 135 atmospheres and steam qualities from 0 to 1.0.

CORRELATION EQUATION

The data of references 1 and 5 to 10 were used herein to develop an empirical relation for the effect of heat addition on void fraction. While all investigators agree that void fraction is a function of heating rate, some question exists as to whether or not void fraction is also a function of flow rate. Reference 9 indicates that flow rate does influence void fraction, whereas references 8 and 10 state that flow rate does not appear to influence void fraction. It should be noted, however, that the flow-rate range of the data in reference 9 covers a factor of 2.5, while that of references 8 and 10 covers a factor of less than 1.4. In view of the inherent widely scattered data (attributable in part to the methods used to measure void fraction), reverse trends, and outright contradictions in the data, especially where the data range is small, it is understandable that opposite conclusions are drawn by the various investigators.

The void fraction is assumed herein to be a function of both heating rate and flow rate. Analysis of the experimental data shows that the combined effect of these variables can be expressed by the ratio of a dimensionless heat-addition parameter Γ to the vapor Reynolds number Re_v. (All symbols are defined in the appendix.) The heat-addition parameter is defined as

$$\Gamma = \frac{qD_h}{\mu_v h_{fg}}$$

In reference 9, the same ratio is expressed as

$$\Gamma = \frac{Q}{wh_{fg}}$$

Analysis of the experimental data also indicates a dependence of void fraction on fluid properties, as characterized by a dependence on fluid pressure. The effect of fluid properties on void fraction was included herein through the use of a dimensionless parameter N_B defined as

$$N_B = \frac{\mu_v^2 \sqrt{g(\rho_l - \rho_v)}}{\rho_v (g_c \sigma_l)^{1.5}} \tag{1}$$

This parameter is used in reference 11 in the correlation of critical-boiling heat-transfer data (see also ref. 12). All properties used in equation (1) are evaluated at the saturation temperature of the fluid that corresponds to the fluid pressure. Values of N_B for water (taken from ref. 11) are shown in figure 1 as a function of the ratio of saturation pressure to critical pressure of the fluid.

All the preceding effects on void fraction, while small and erratic over the limited range of conditions included in the available data, appear necessary for a correlation.

The empirical equation presented in reference 2 is

$$\frac{1}{x} = 1 - \left(\frac{1}{\beta}\right)^{0.67} \left[1 - \left(\frac{1}{\alpha}\right)^{(1/\beta)^{0.1}}\right] \tag{2}$$

or

$$\alpha^{(1/\beta)^{0.1}} = \frac{1}{1 + \left(\frac{1 - x}{x}\right)\beta^{0.67}} \tag{3}$$

Modification of equations (2) and (3) to include the effects of the heat-addition parameter, the vapor Reynolds number, and the fluid-property parameter on void fraction resulted in the following empirical equation:

$$\frac{1}{x} = 1 - \left(\frac{1}{\beta}\right)^{\left(\frac{0.70}{1+(\Gamma/Re_V)^{0.53\times10^6 N_B}}\right)}\left[1 - \left(\frac{1}{\alpha}\right)^{(1/\beta)^{(0.1+\beta)}}\right] \tag{4}$$

or

$$\alpha^{(1/\beta)^{(0.1+\beta)}} = \frac{1}{1 + \left(\frac{1 - x}{x}\right)\beta^{\left(\frac{0.70}{1+(\Gamma/Re_V)^{0.53\times10^6 N_B}}\right)}} \tag{5}$$

COMPARISON OF RESULTS FROM PRESENT WORK WITH EXPERIMENTAL DATA

When two-phase flow without heat addition exists (one-component flow, $q = 0$), a comparison of equations (3) and (5) shows that the difference between them is in the exponents of the density term β, which has been increased from 0.67 to 0.70, and of the void-fraction term α, which has been changed from $(1/\beta)^{0.1}$ to $(1/\beta)^{(0.1+\beta)}$. The change in the exponent of β is of significance primarily for low fluid pressures. On the other hand, the change in the exponent of α becomes increasingly more significant with increasing fluid pressure.

A comparison of the calculated values of void fraction with no heat addition from equations (3) and (5) and experimental data is shown in figure 2 as a function of steam quality for fluid pressures of 14.7, 1000, and 1180 pounds per square inch absolute (refs. 5 to 7, respectively). The void-fraction values calculated from equation (5) are somewhat higher than those calculated from equation (3); however, both sets of calculated values of void fraction represent the experimental data quite well.

As a matter of interest, the present work is also compared with the analytical study of reference 4 in figure 3. In reference 4 a new analytical two-phase mixing-length model is described that consists of a two-phase system treated as a continuous medium, and the methods and assumptions commonly used in a single-phase turbulent flow are applied. Void fractions with no heat addition calculated by using the equations and concepts obtained from this mixing-length model are shown. The calculated curves (ref. 4) in figure 3 are plotted in terms of the variation of void fraction with steam quality for fluid pressures of 163.5 and 613 pounds per square inch absolute. The analytical curves from reference 4 yield higher void fractions at a given steam quality than those previously reported by the same author in reference 13 and are shown for comparison in figure 3(b). The results of reference 4 are also in good agreement with those of reference 3. Also shown in figure 3 are curves calculated by using equation (5) of the present investigation. It is apparent that for no heat addition the analytical void-fraction calculations of reference 4 and those of the present inventigation are in excellent agreement.

In order to illustrate the magnitude of the overall effect of heat addition on void fraction, the variation of void fraction with steam quality with the use of equation (5) is shown in figure 4 for heat-addition-parameter values of 0, 10^{-3}, 10^{-2}, and 5×10^{-2} and fluid pressures of 115, 615, and 2000 pounds per square inch absolute. The steam quality for values less than 0.1 is plotted in Cartesian coordinates in order to provide an expanded scale in this quality region, while at steam qualities greater than 0.1 logarithmic coordinates are used. Cartesian coordinates are used at all times for the void fraction (ordinate). The calculated curves show that the void fraction for a given steam quality decreases with increasing heat-addition parameter. For example, at a fluid pressure of 115 pounds per square inch absolute and a steam quality of 0.02, the void fraction decreases from 0.65 to 0.42 (35-percent reduction) as the heat-addition parameter increases from 0 to 5×10^{-2}. For steam-quality values greater than 0.1, the percent change in the void fraction becomes increasingly less for the same range of heat-addition-parameter values (the change is zero at $x = 1.0$.)

It is also apparent from figure 4 that with increasing pressure level the void fraction decreases at a given steam quality. At the critical pressure for water, the ratio of vapor to liquid density is 1.0; consequently, the void fraction varies linearly with steam quality, and the effect of heat addition drops out of the equation.

In the available experimental data with heat addition (refs. 1 and 8 to 10) the heat-addition parameter Γ/Re_V varies from approximately 10^{-4} to 10^{-3}. In the lower portion of this range ($\Gamma/Re_V = 10^{-4}$) the heat-addition parameter can be changed by ±50 percent without significantly affecting the void fraction.

A comparison of the calculated void-fraction values obtained with equation (5) and the experimental data of references 1 and 8 to 10 is shown in figures 5 to 8 as a function of steam quality. It is apparent that the calculated values of void fraction represent the experimental data quite well considering the scatter inherent in the experimental data.

The use of the fluid-property parameter N_B was of particular significance in achieving a good correlation of the calculated curve with the data at a fluid pressure of 2000 pounds per square inch absolute.

The present work does not differentiate between horizontal and vertical flow data; the gross techniques used in obtaining the data, as well as the limited range of conditions covered, are such as to preclude any final conclusions in regard to the significance of channel orientation on void fraction at this time. It is apparent, however, from the data shown in figures 2 and 5 to 8 that the present work appears to be applicable, at least for engineering purposes, to either type of flow. Furthermore, the present work applies reasonably well to multiple channels of other than circular cross section (see figs. 5 and 7).

CONCLUDING REMARKS

The present empirical correlation of void-fraction data is limited by the relatively meager quantity of data with heat addition available in the literature (in terms of heating rate, flow rate, tube geometry, orientation, etc.). More important, the correlation is limited by the lack of single-component two-phase void-fraction data for fluids other than steam-water flow. Fluids with properties that are much different from steam-water flow should be studied in order to establish the validity of the use of the heat-addition and the fluid-property parameters introduced herein.

It should also be noted that the present work does not consider the case of local nucleate boiling (no net vapor generation). Furthermore, this correlation does not consider the effect of subcooling of the liquid at the entrance to the heated tube or channel. The present work, therefore, should be applied only to a saturated fluid flowing through a heated tube or channel.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 10, 1962

APPENDIX - SYMBOLS

D_h hydraulic diameter, ft

G mass velocity, lb_{mass}/hr, sq ft

g acceleration (gravity), 4.17×10^8 ft/hr^2

g_c conversion constant between lb_{force} and lb_{mass}, 4.17×10^8 $(lb_{mass}/lb_{force})(ft/hr^2)$

h_{fg} latent heat of fluid, Btu/lb_{mass}

N_B fluid-property parameter, $\dfrac{\mu_v^2\sqrt{g(\rho_l - \rho_v)}}{\rho_v(g_c\sigma_l)^{1.5}}$, dimensionless

P fluid pressure, lb/sq in. abs

Q heat flux, Btu/hr

q heat flux per unit surface area, Btu/(hr)(sq ft)

Re_v vapor Reynolds number, GD_h/μ_v, dimensionless

w weight flow, lb_{mass}/hr

x fluid (steam) quality, dimensionless

α void fraction, dimensionless

β ratio of vapor to liquid density, dimensionless

μ fluid viscosity, lb_{mass}/(hr)(ft)

ρ fluid density, lb_{mass}/cu ft

σ_l fluid surface tension, lb_{force}/ft

Γ heat-addition parameter, $qD_h/\mu_v h_{fg}$, dimensionless

Subscripts:

cr critical

l liquid

s saturation

v vapor

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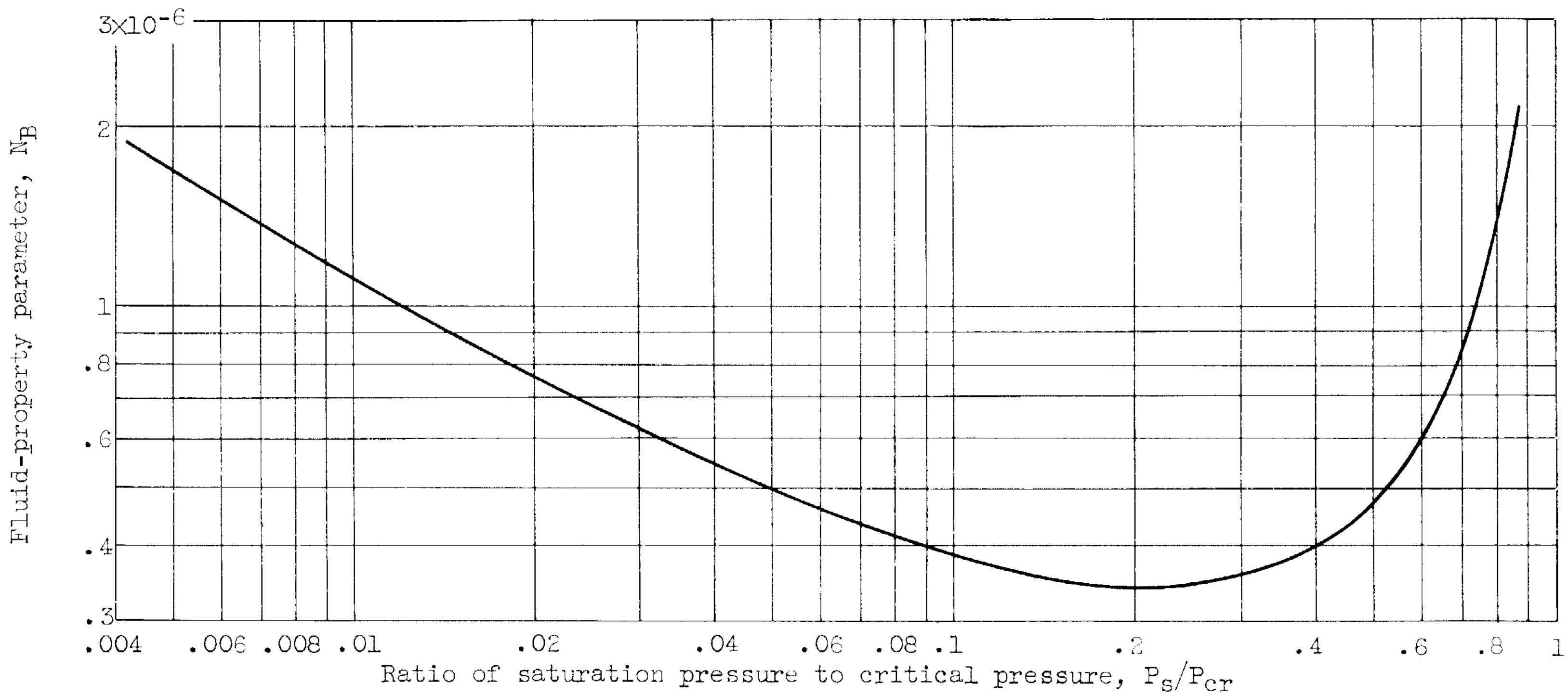
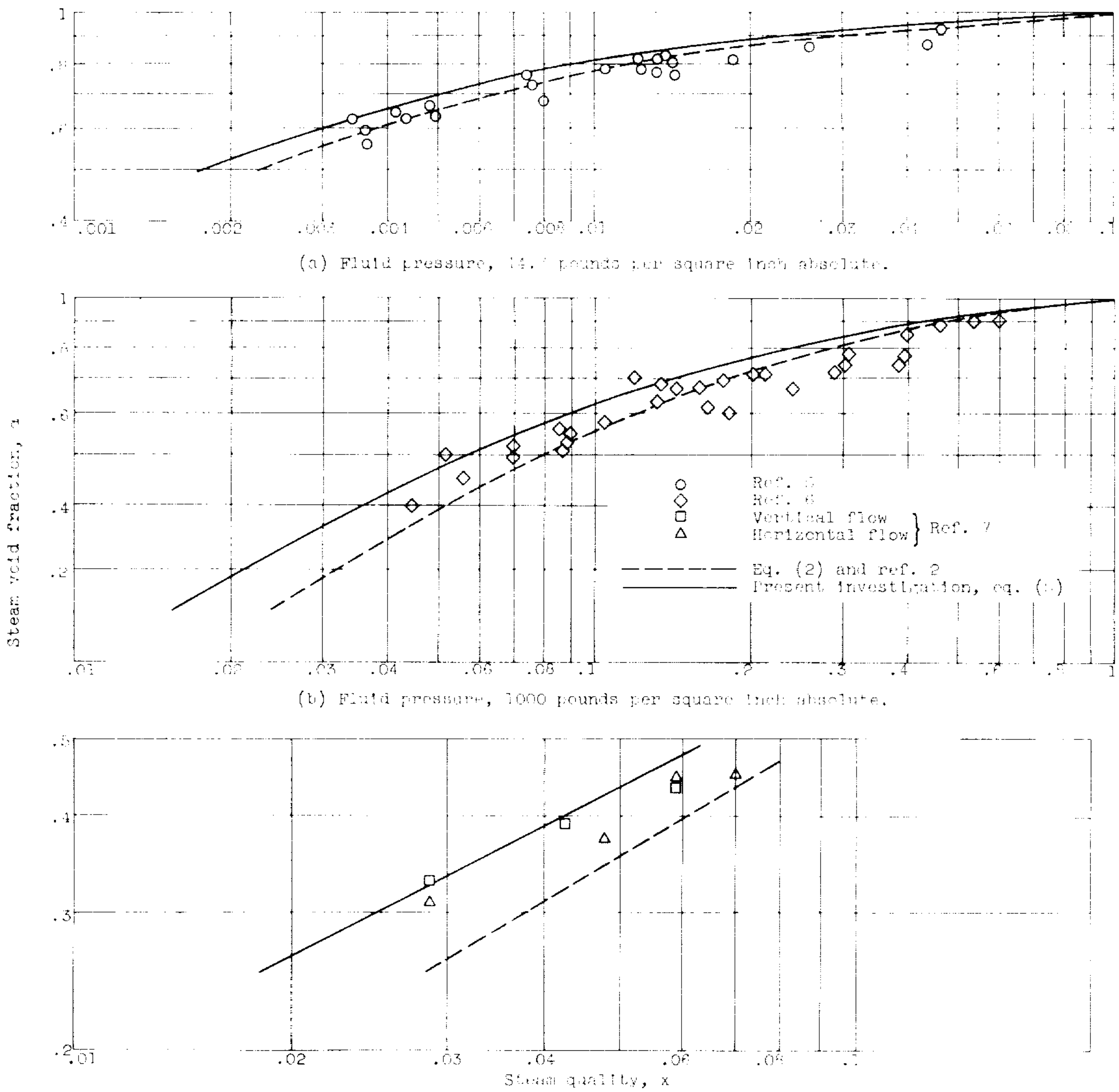


Figure 1. - Variation of fluid-property parameter for water with ratio of saturation pressure to critical pressure of fluid (ref. 11).

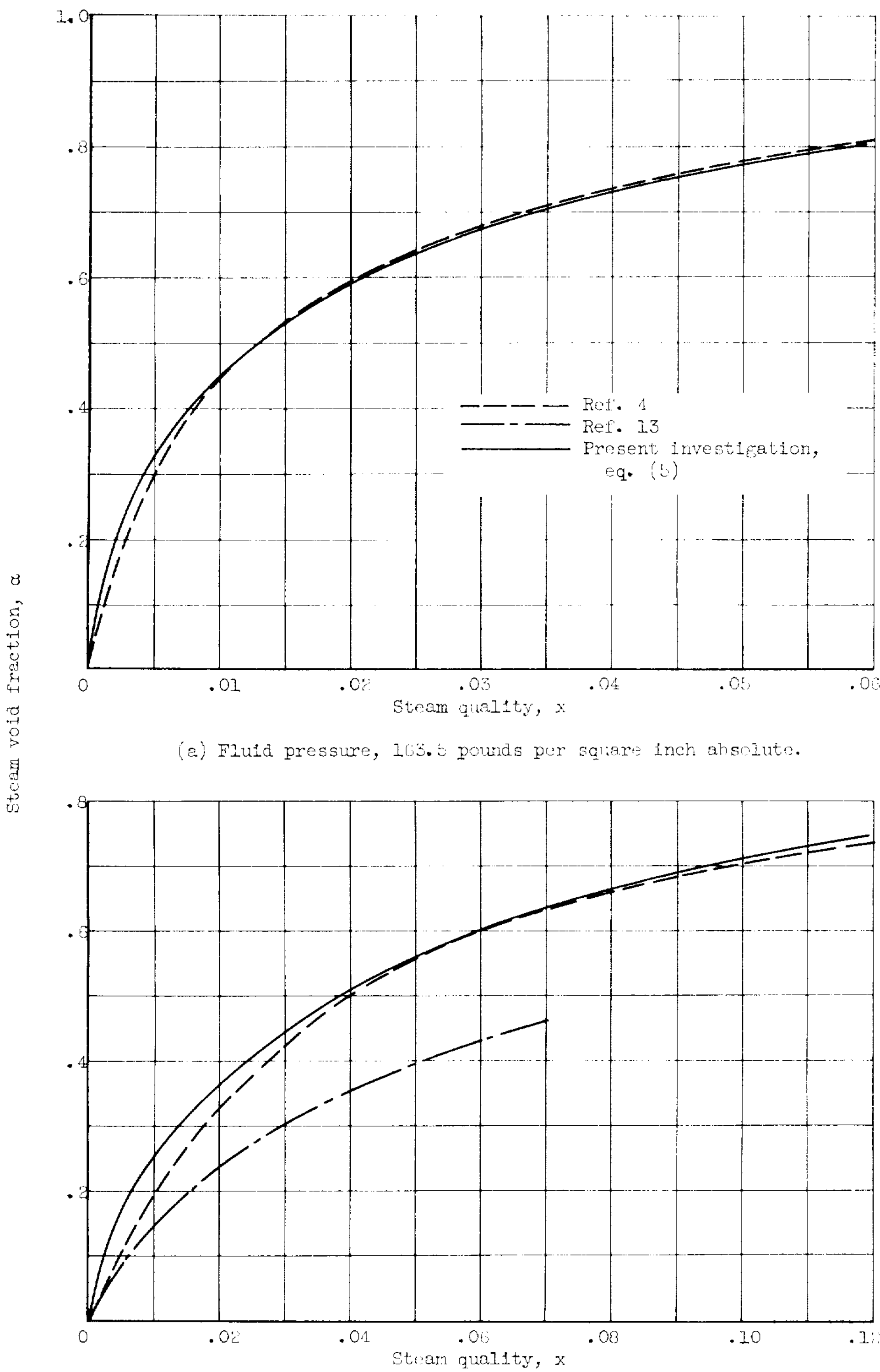


(a) Fluid pressure, 14.7 pounds per square inch absolute.

(b) Fluid pressure, 1000 pounds per square inch absolute.

(c) Fluid pressure, 1180 pounds per square inch absolute.

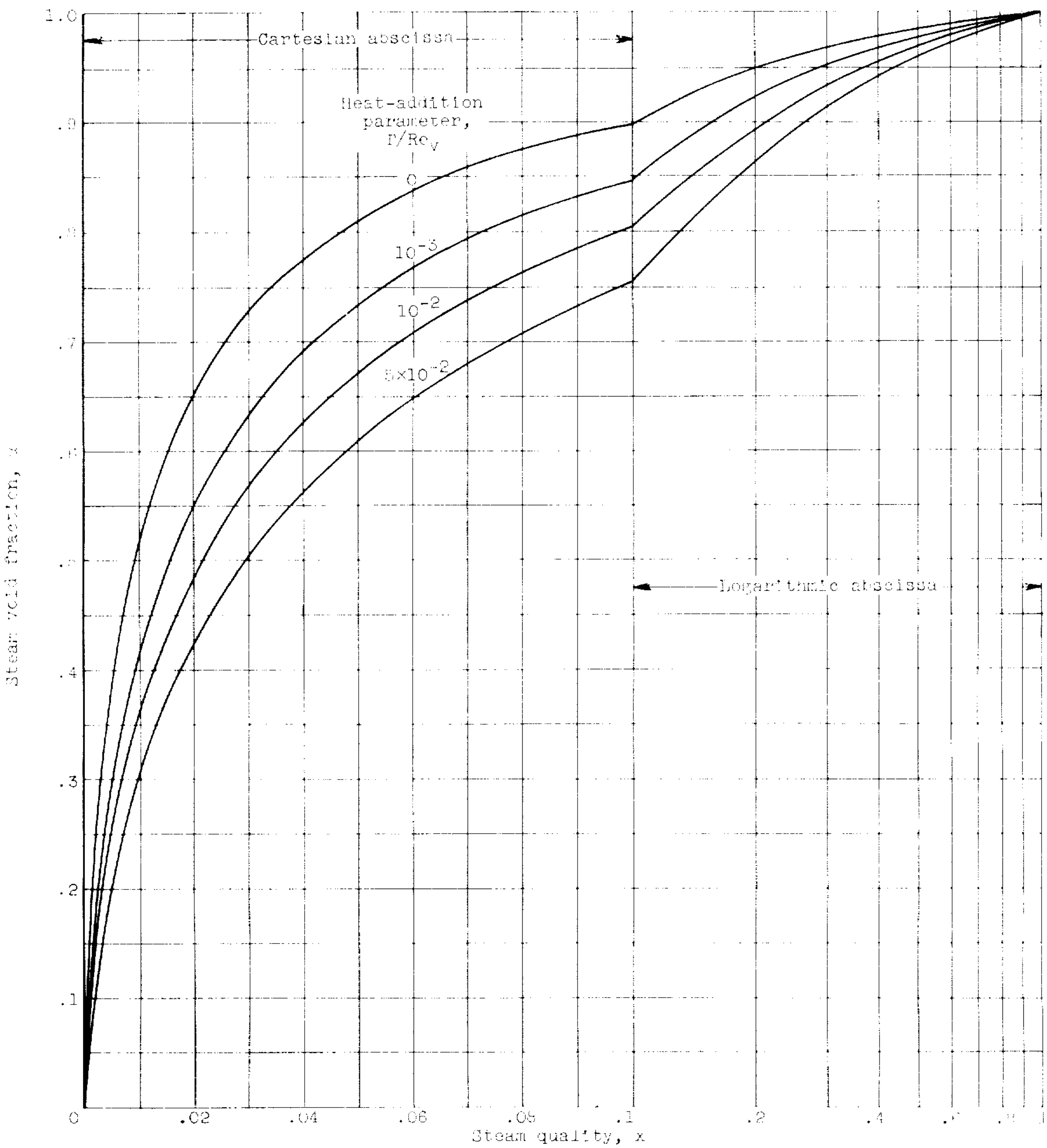
Figure 2. - Comparison of values of void fraction with no heat addition calculated from equation (5) with experimental data and with those calculated from equation (2) of reference 2.



(a) Fluid pressure, 163.5 pounds per square inch absolute.

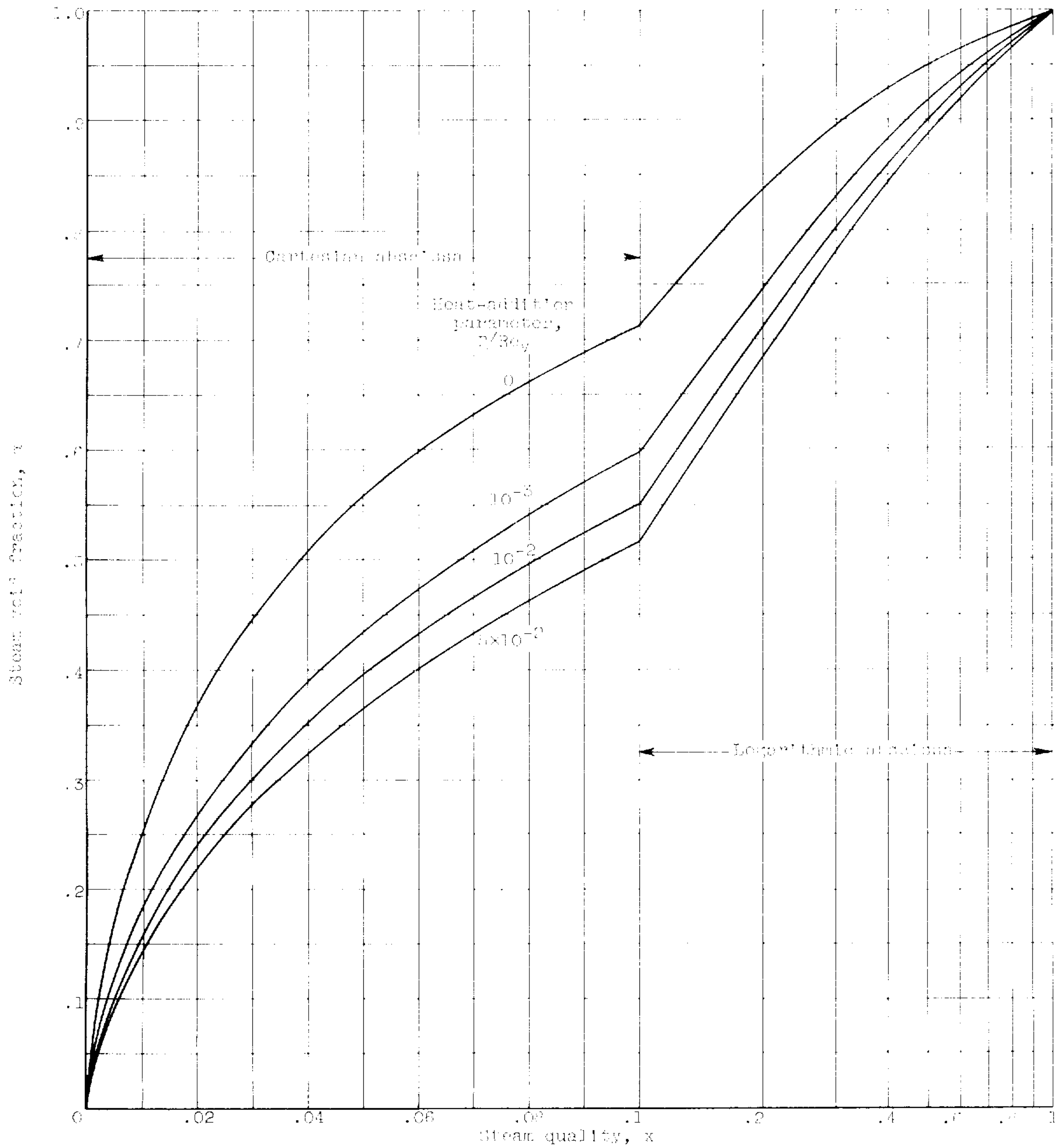
(b) Fluid pressure, 615 pounds per square inch absolute.

Figure 3. - Comparison of void-fraction values with no heat addition calculated from equation (5) with analytical studies of references 4 and 13.



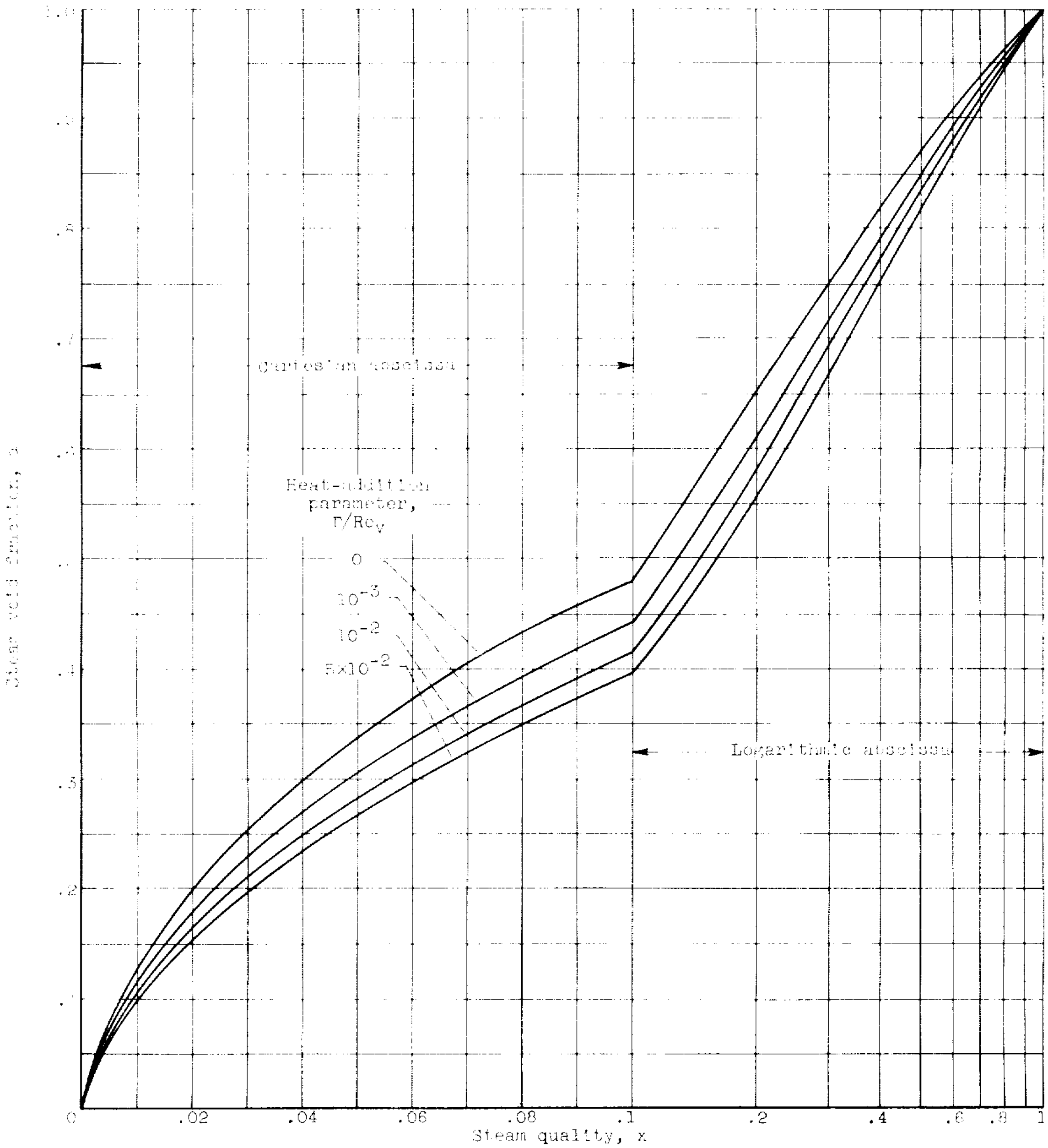
(a) Fluid pressure, 115 pounds per square inch absolute.

Figure 4. - Typical effect of heat addition on void fraction calculated from equation ([illegible]) as function of fluid quality.



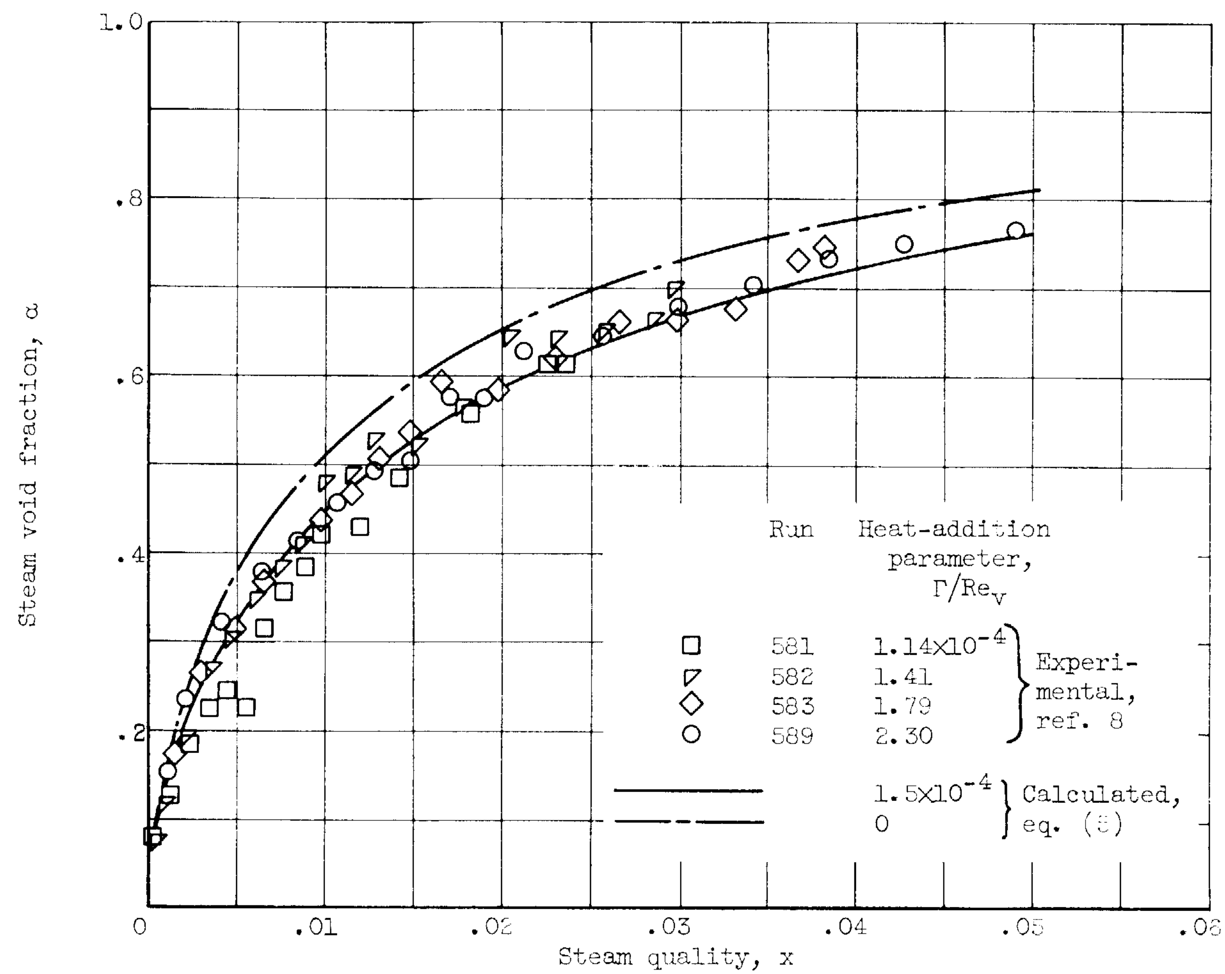
(b) Fluid pressure, 615 pounds per square inch absolute.

Figure 4. - Continued. Typical effect of heat addition on void fraction calculated from equation (5) as function of fluid quality.



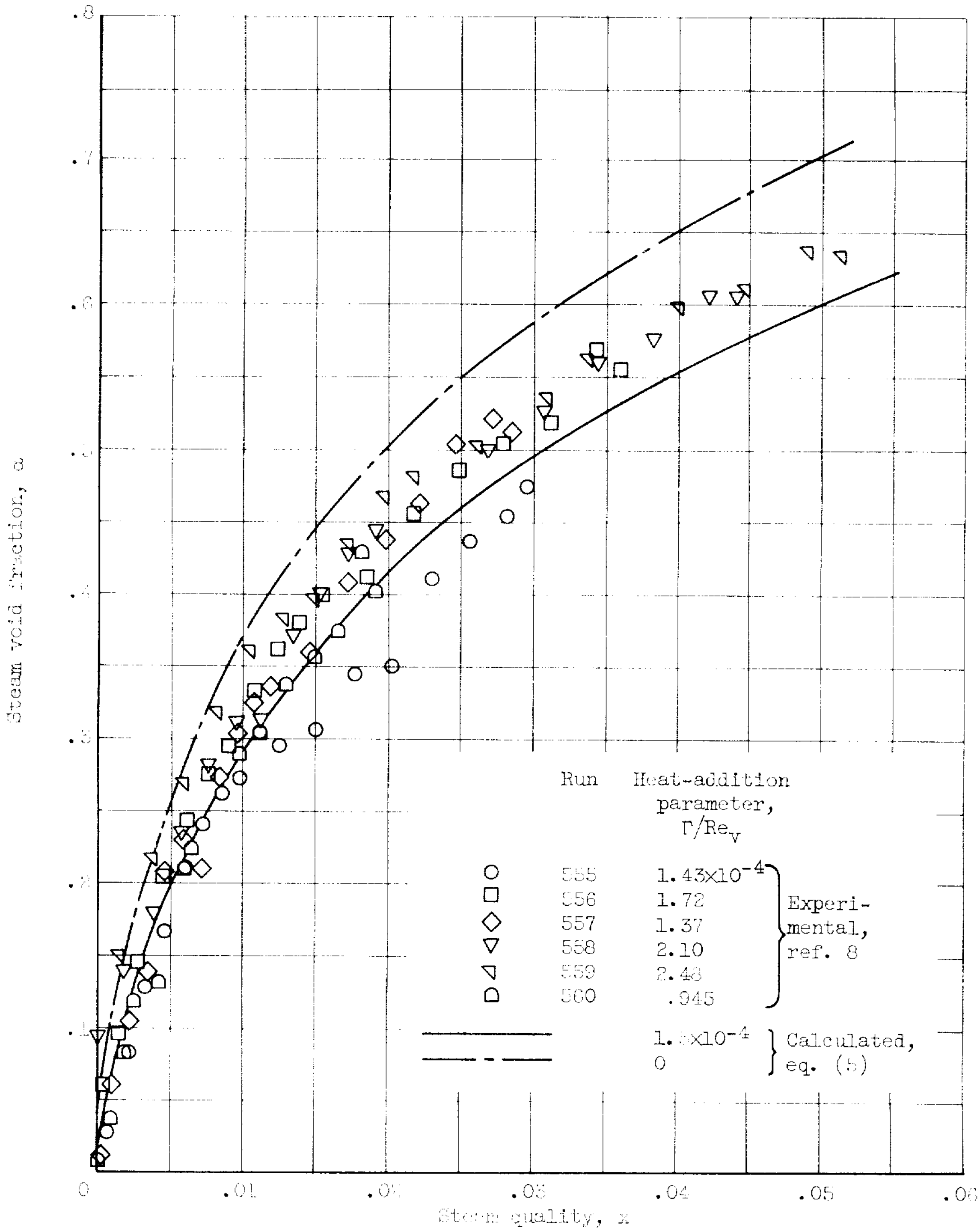
(c) Fluid pressure, 2000 pounds per square inch absolute.

Figure 4. - Concluded. Typical effect of heat addition on void fraction calculated from equation (F) as function of fluid quality.



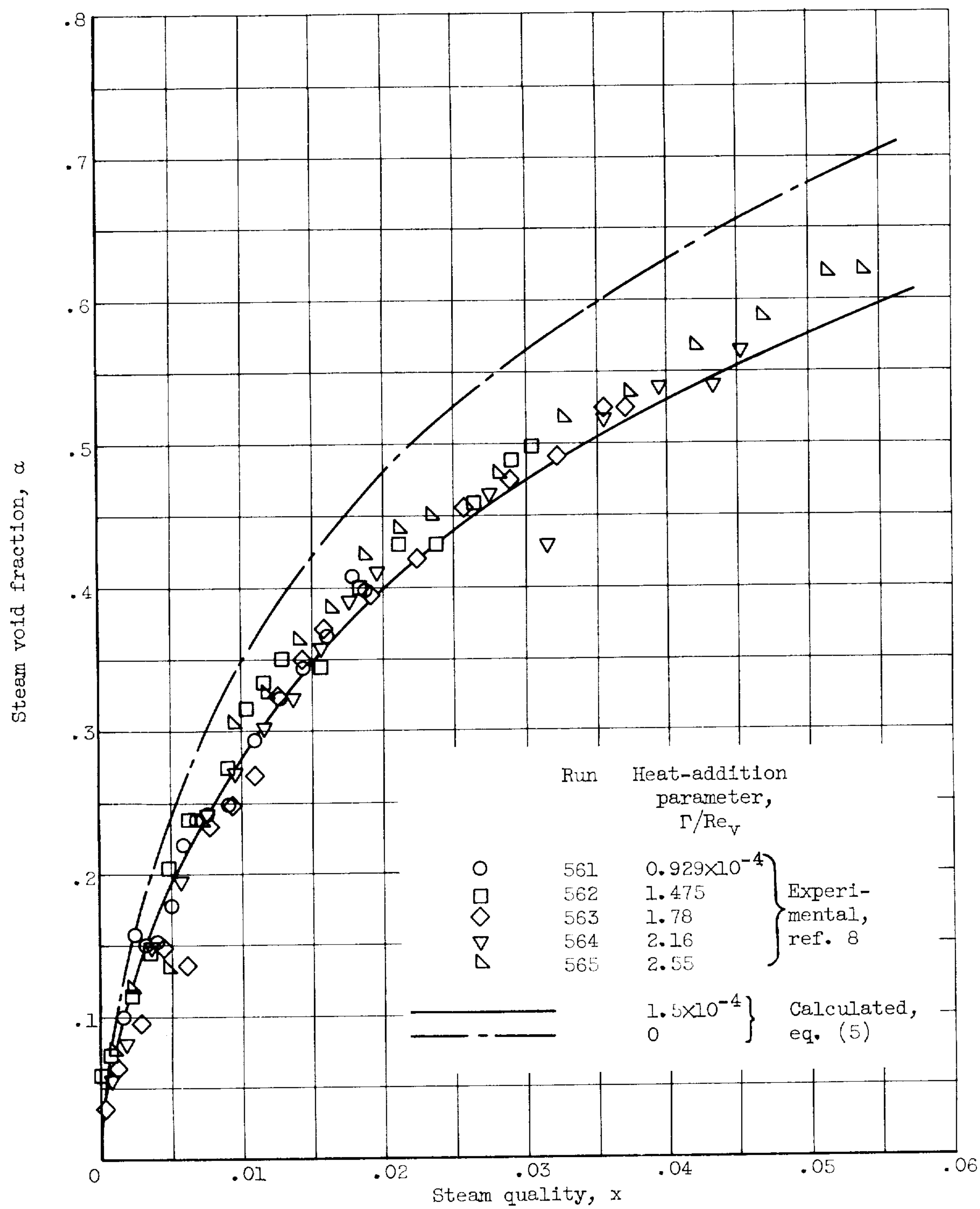
(a) Fluid pressure, 115 pounds per square inch absolute.

Figure 5. - Comparison of void-fraction values calculated from equation (8) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



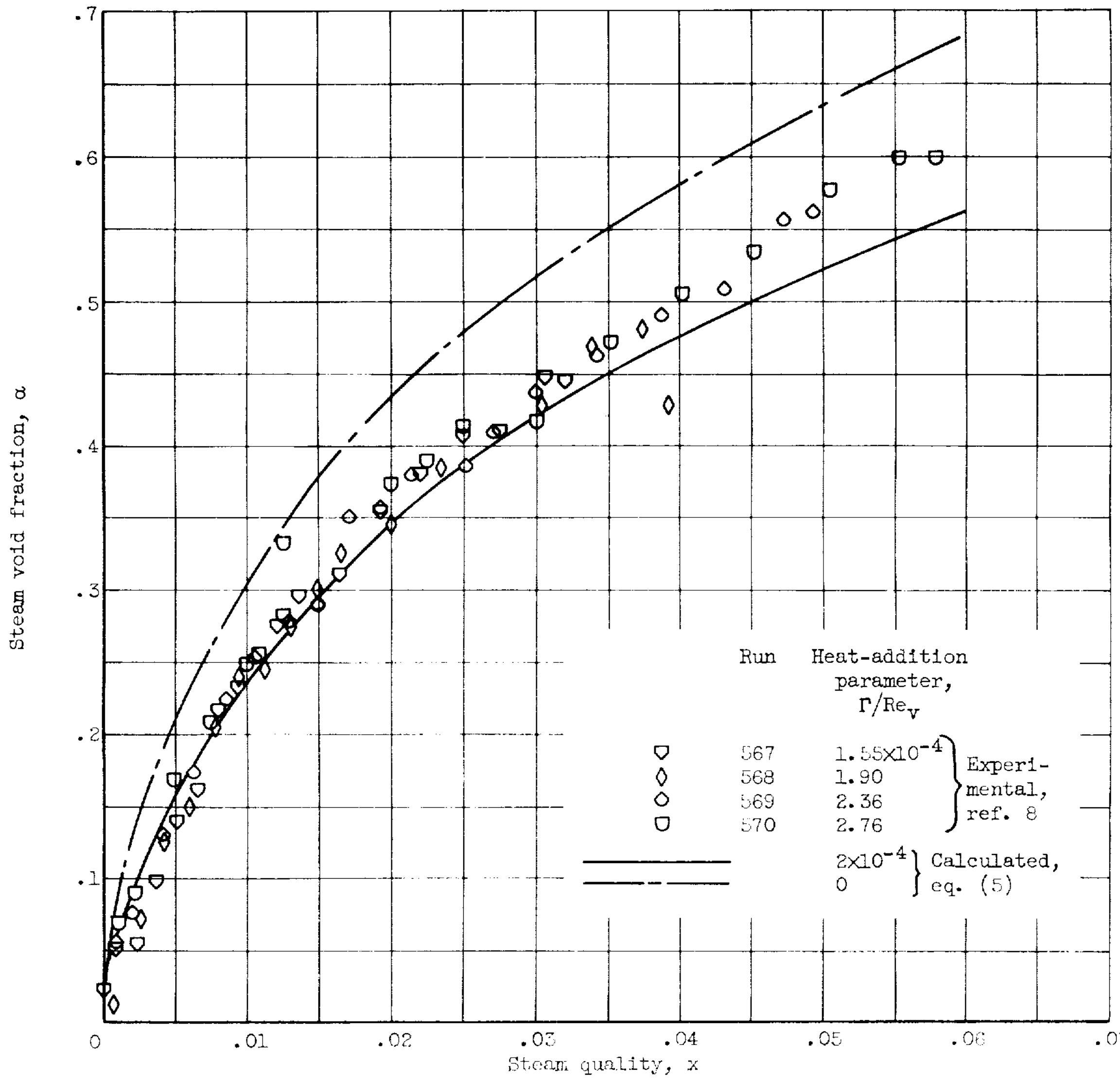
(b) Fluid pressure, 275 pounds per square inch absolute.

Figure 5. - Continued. Comparison of void-fraction values calculated from equation (5) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



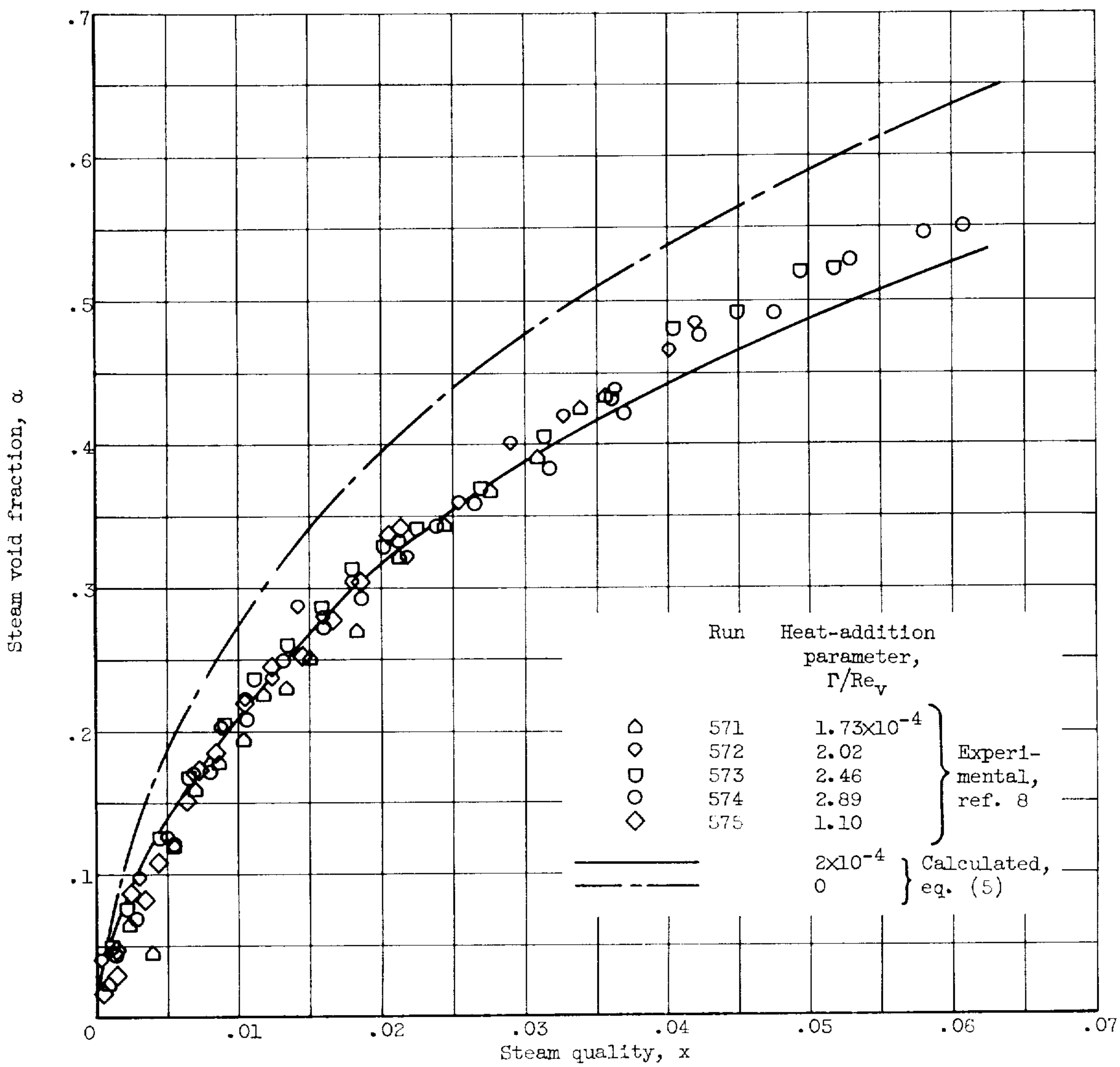
(c) Fluid pressure, 315 pounds per square inch absolute.

Figure 5. - Continued. Comparison of void-fraction values calculated from equation (5) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



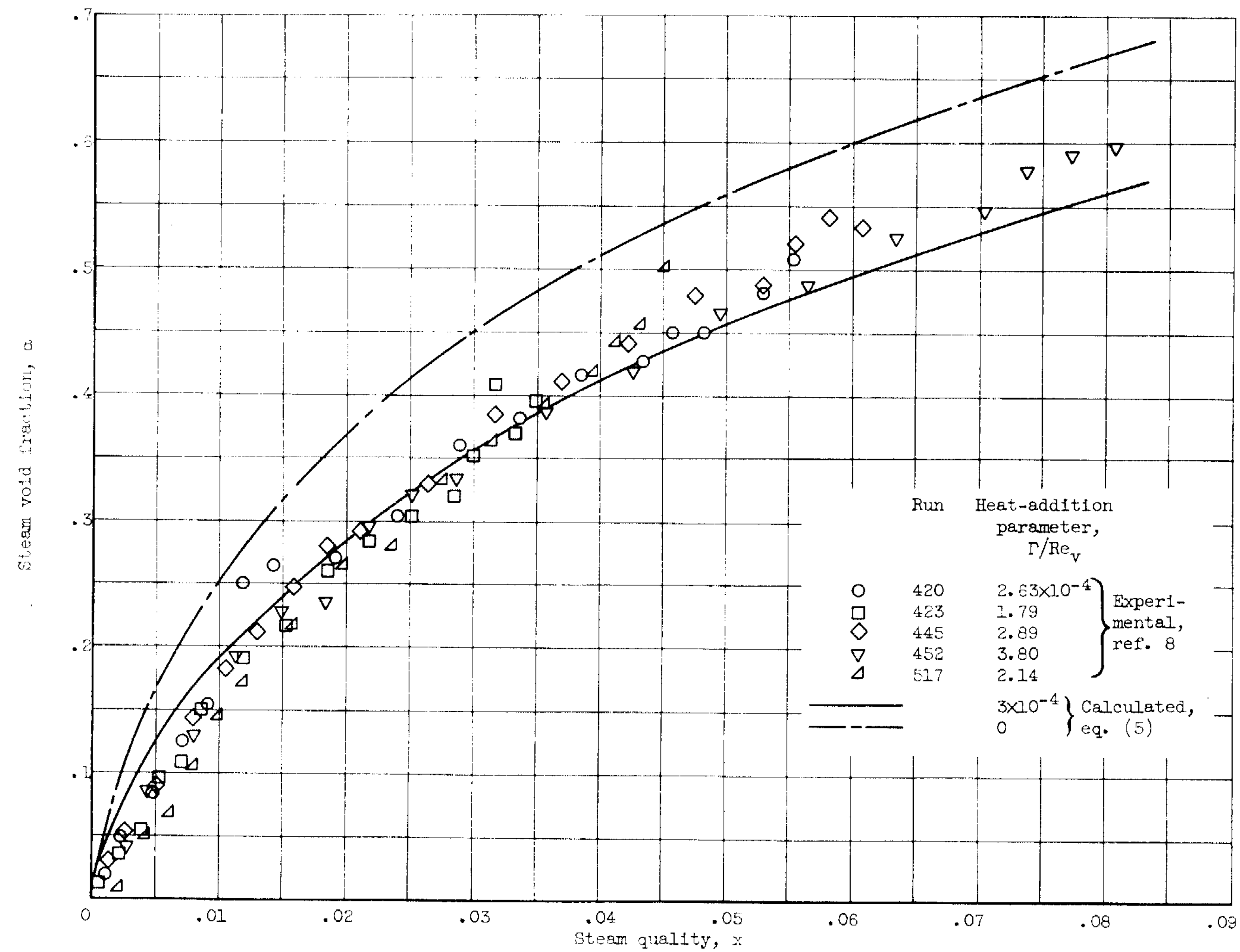
(d) Fluid pressure, 415 pounds per square inch absolute.

Figure 5. - Continued. Comparison of void-fraction values calculated from equation (5) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



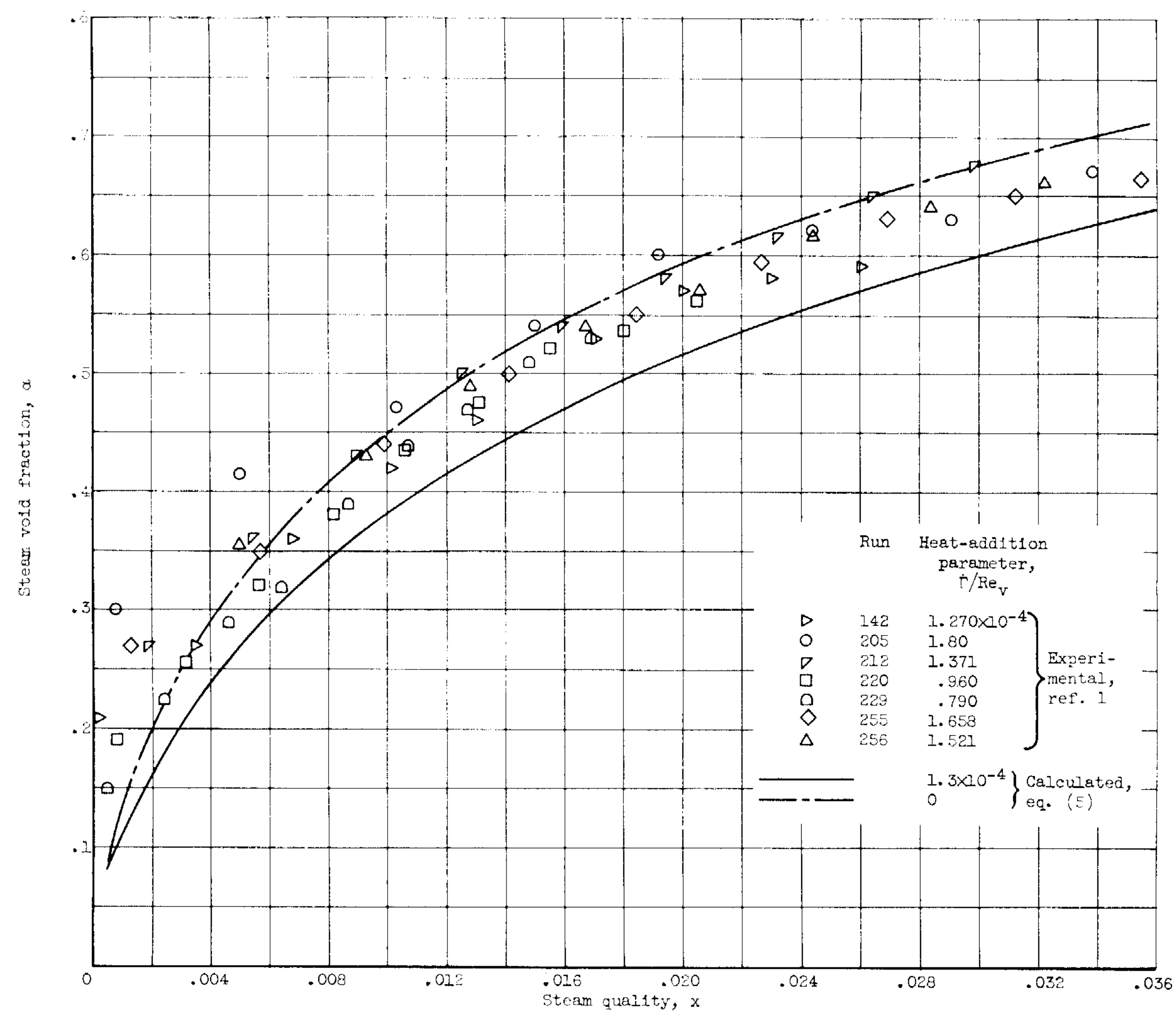
(e) Fluid pressure, 515 pounds per square inch absolute.

Figure 5. - Continued. Comparison of void-fraction values calculated from equation (5) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



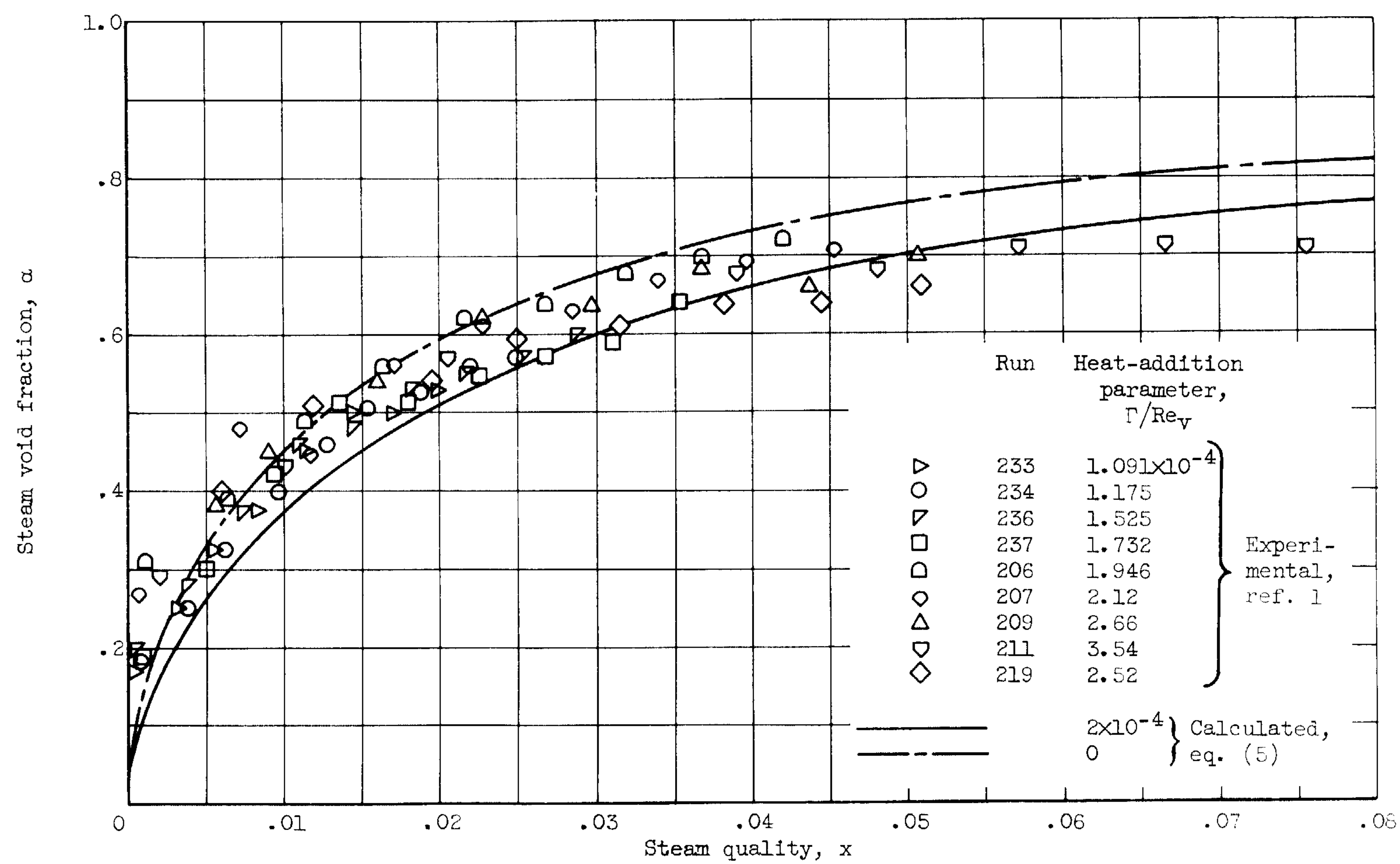
(f) Fluid pressure, 615 pounds per square inch absolute.

Figure 5. - Concluded. Comparison of void-fraction values calculated from equation (5) with experimental data for various heat additions, mass velocities, and fluid pressures. Multiple rectangular channels.



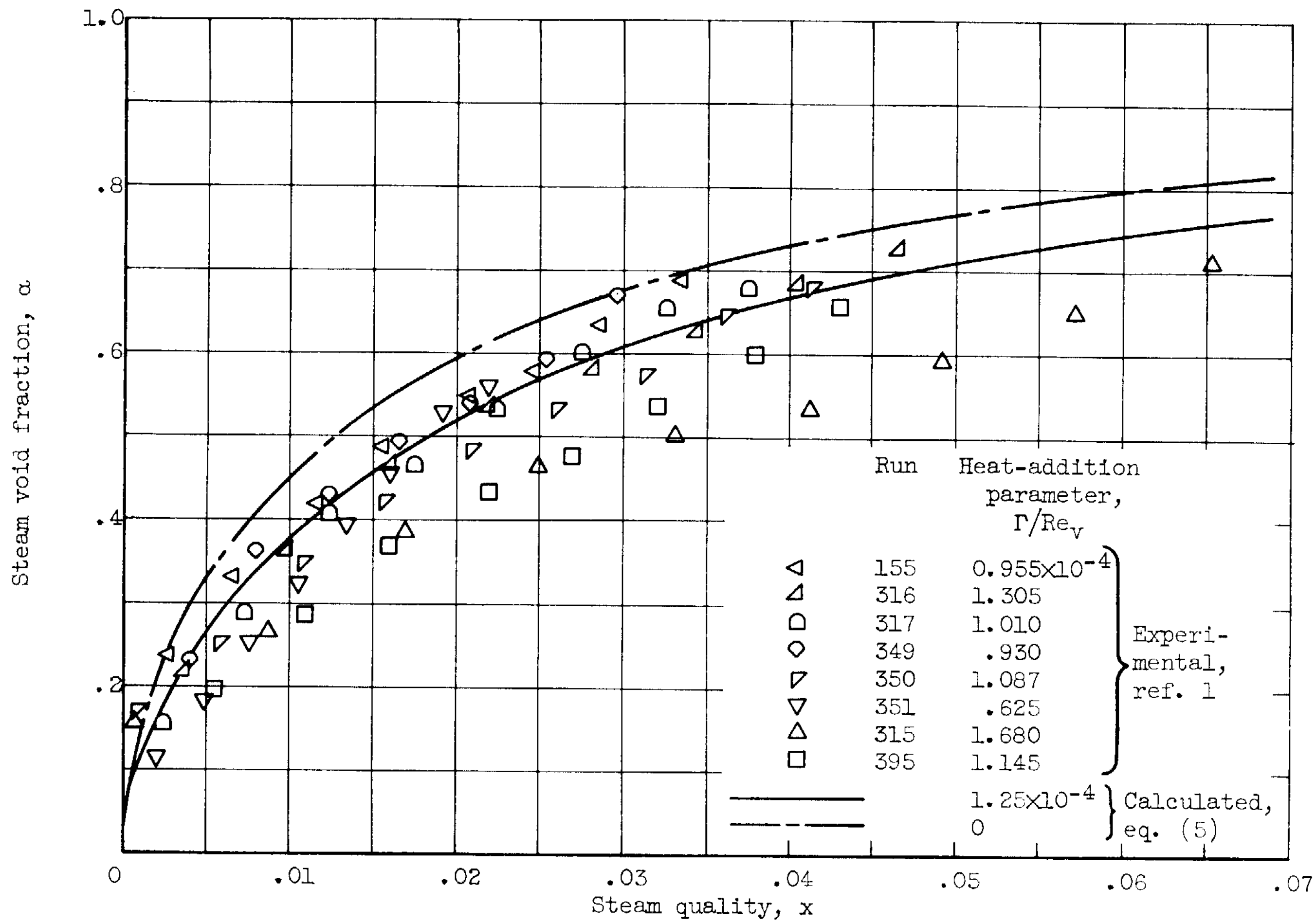
(a) Fluid pressure, 163 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.5 inch.

Figure 6. - Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



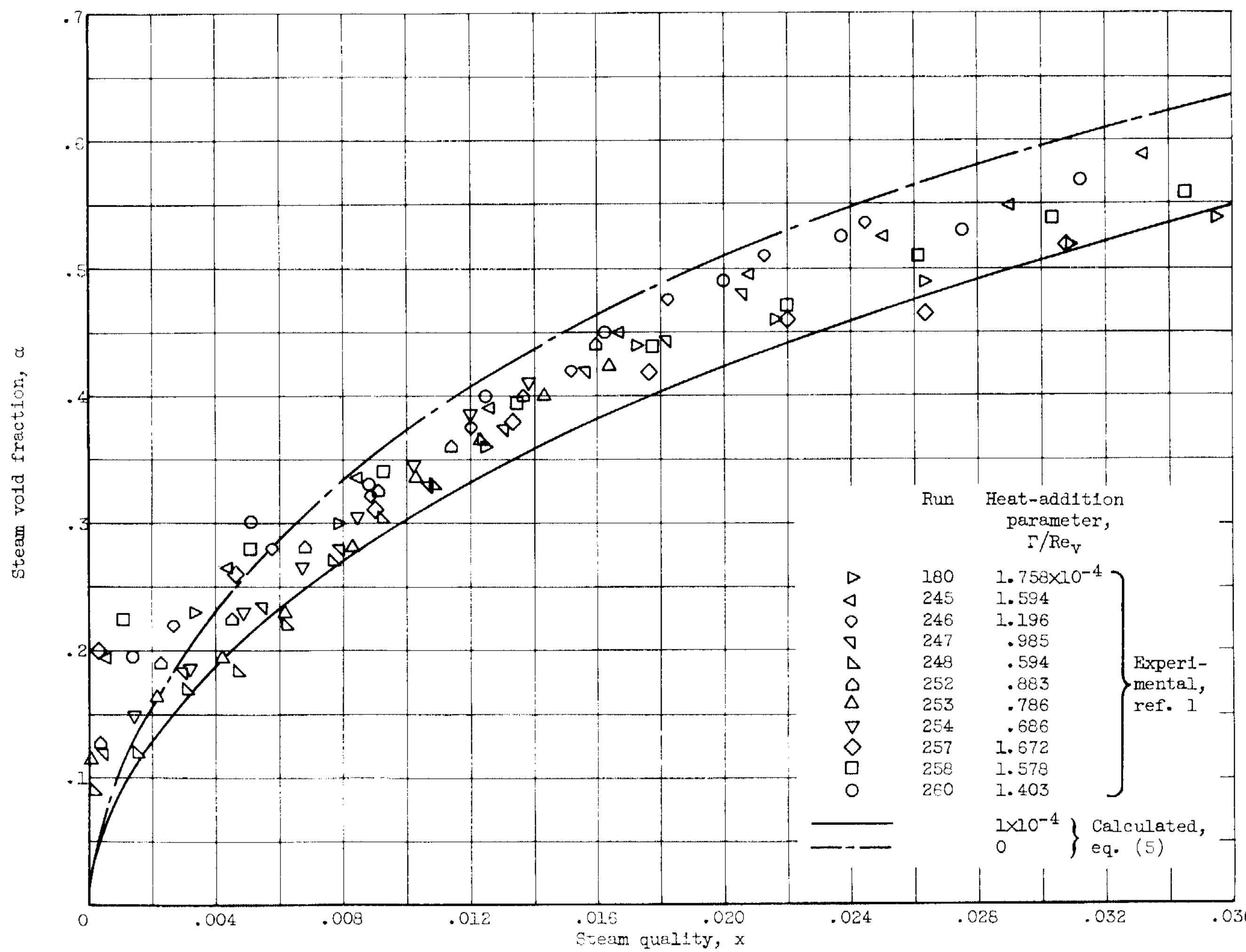
(b) Fluid pressure, 163 pounds per square inch absolute; restricted natural circulation; tube diameter, 0.5 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



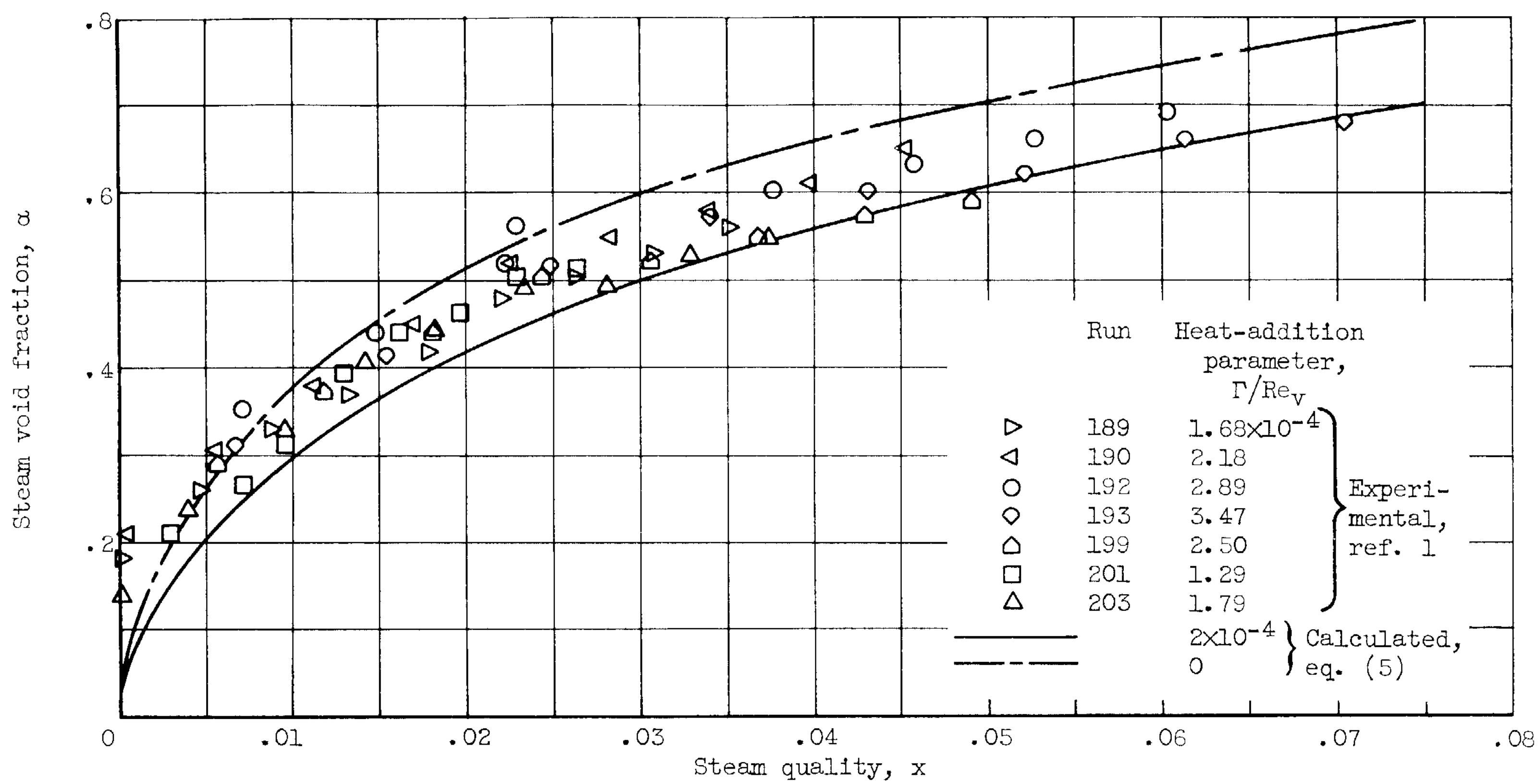
(c) Fluid pressure, 163 pounds per square inch absolute; forced flow; tube diameter, 0.25 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



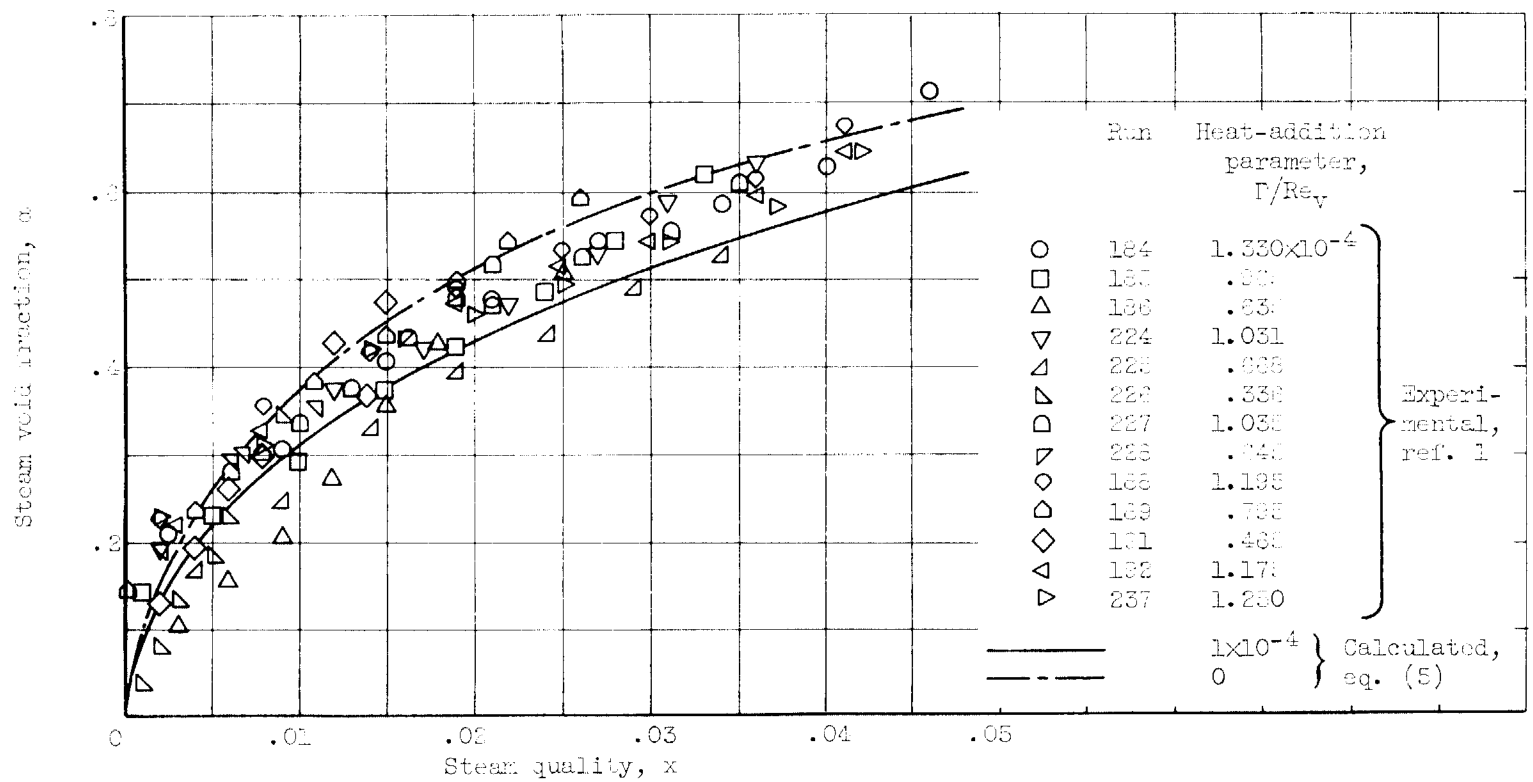
(d) Fluid pressure, 263 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.5 inch.

Figure 8. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



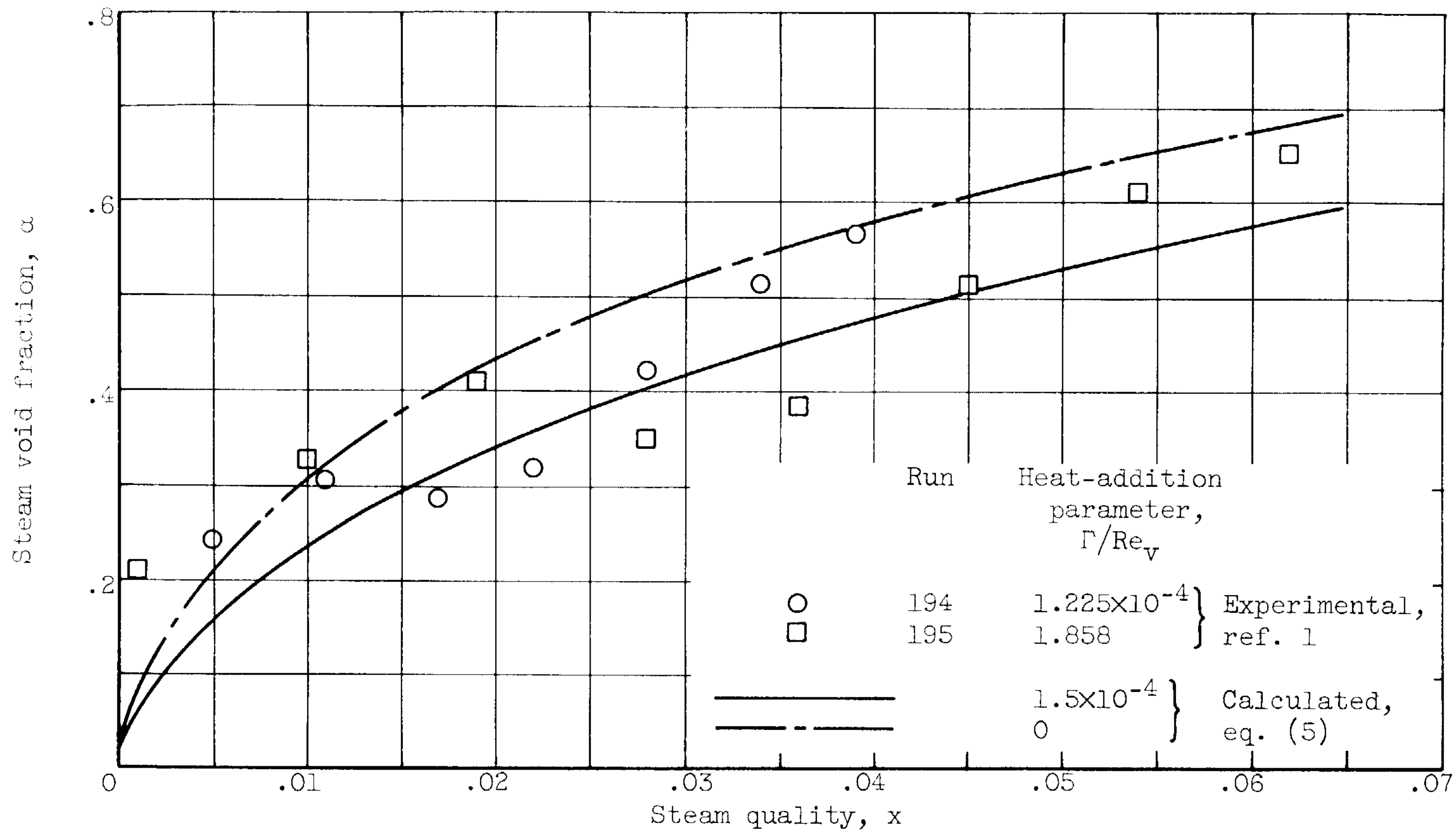
(e) Fluid pressure, 263 pounds per square inch absolute; restricted natural circulation; tube diameter, 0.5 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



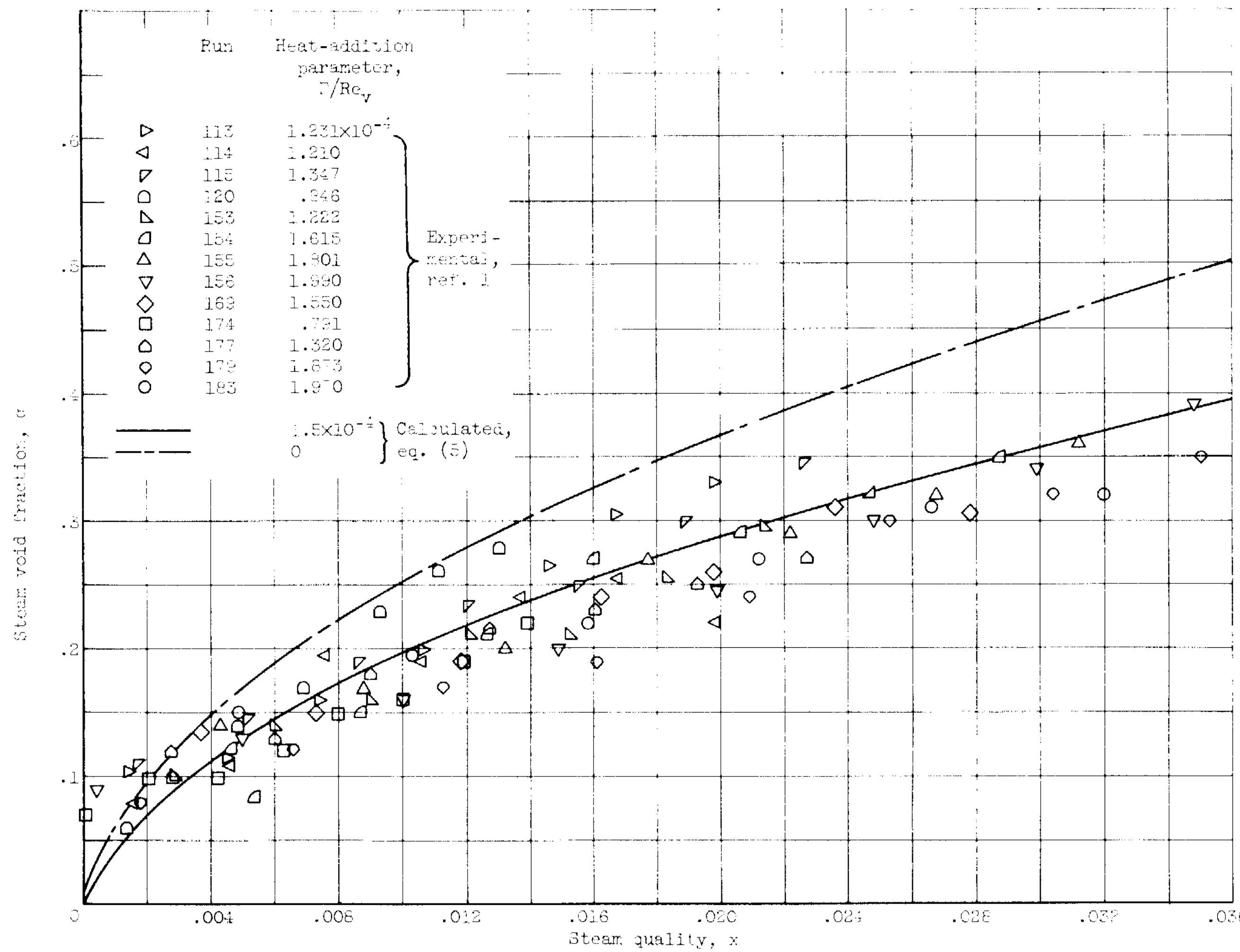
(f) Fluid pressure, 263 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.[illegible] inch.

Figure [illegible]. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



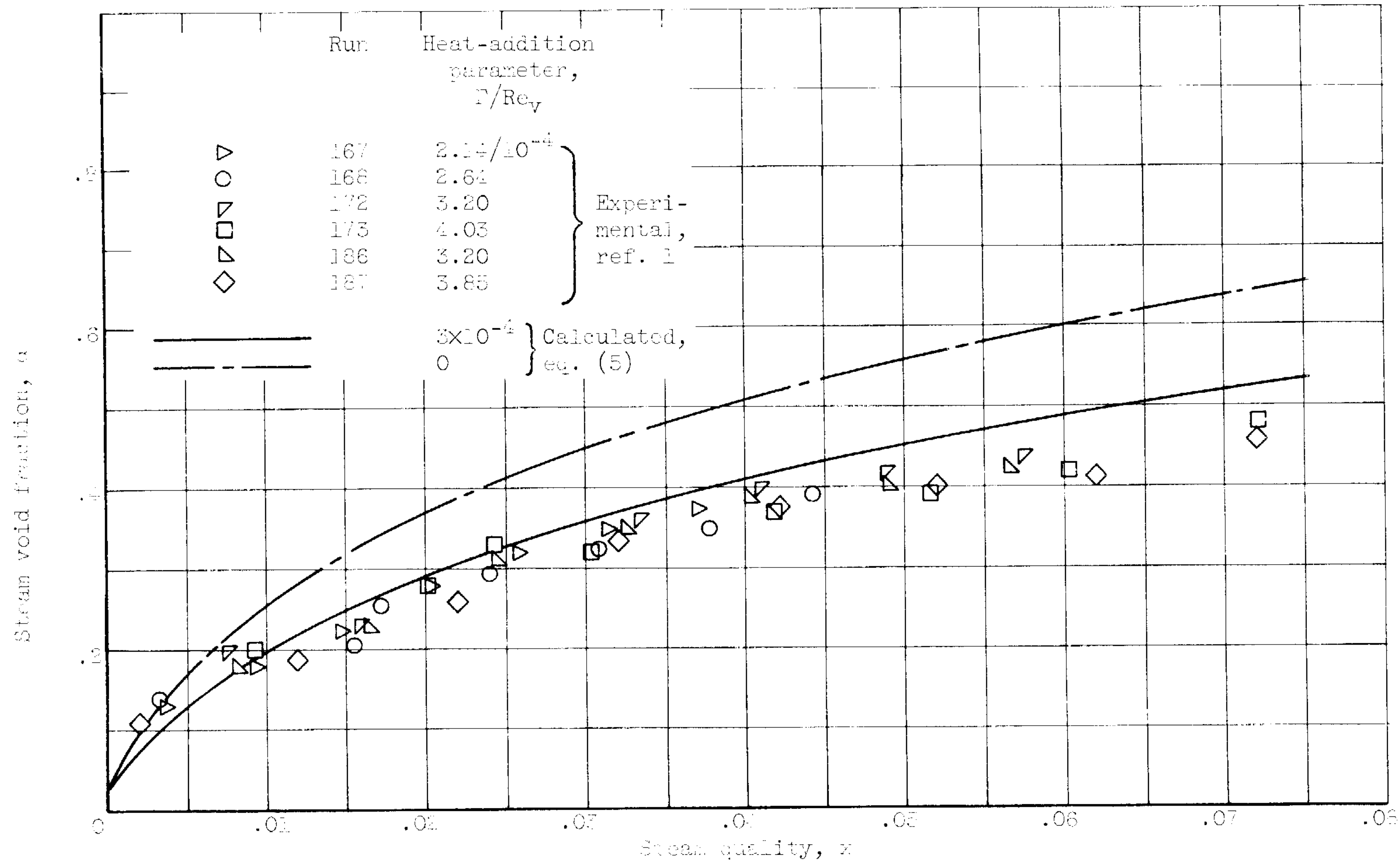
(g) Fluid pressure, 413 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.25 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



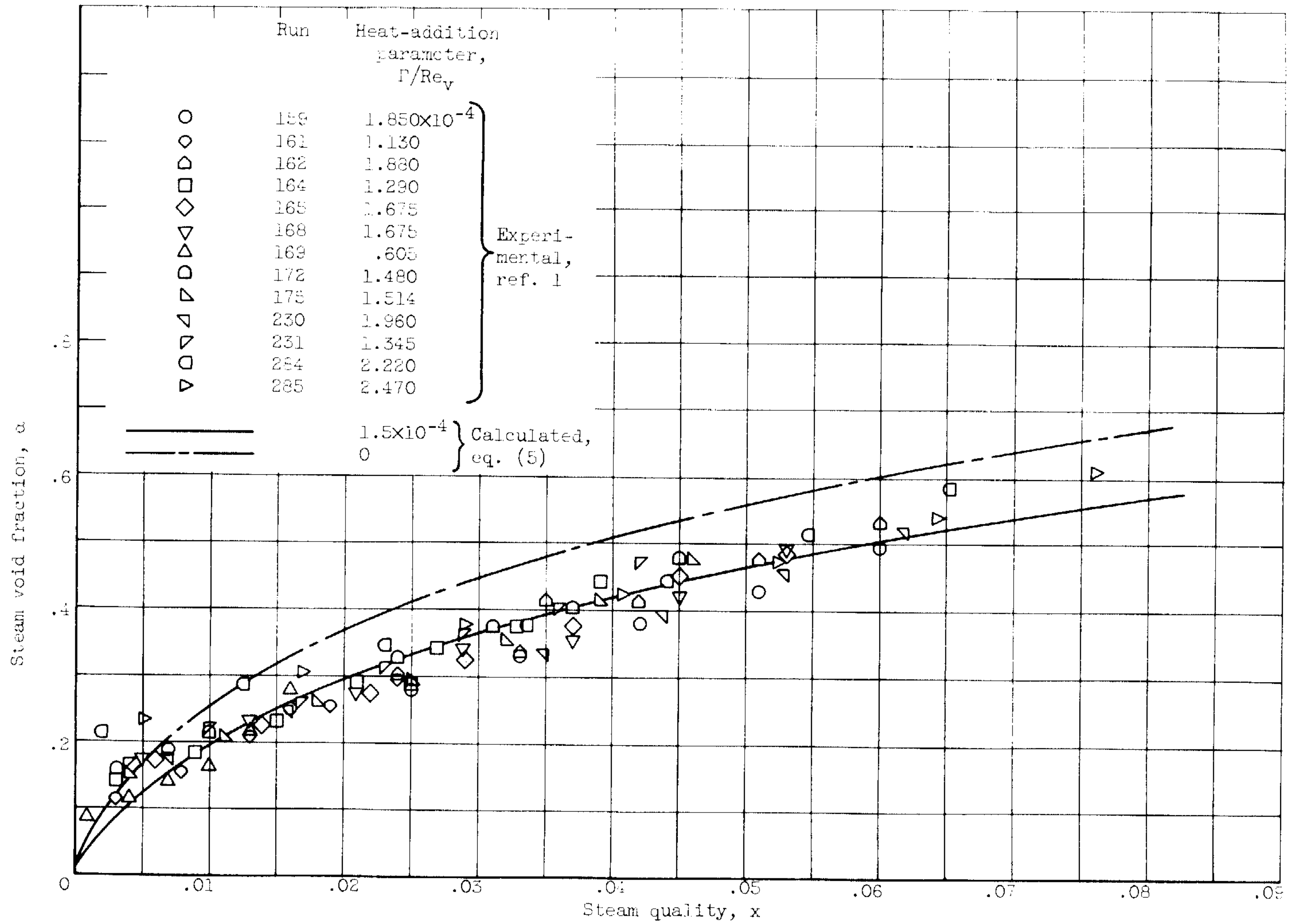
(h) Fluid pressure, 613 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.5 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



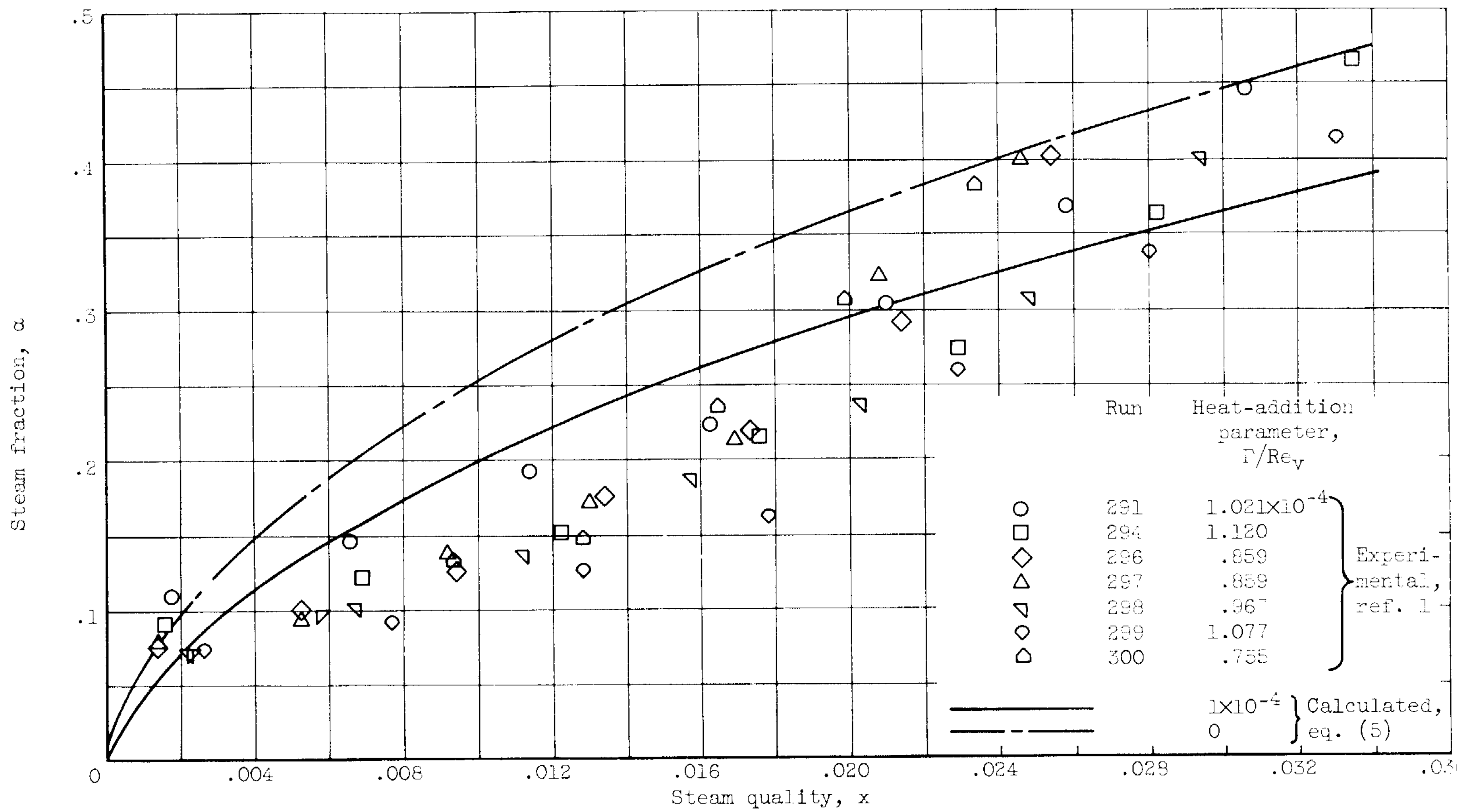
(i) Fluid pressure, 615 pounds per square inch absolute; restricted natural circulation; tube diameter, 0.5 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



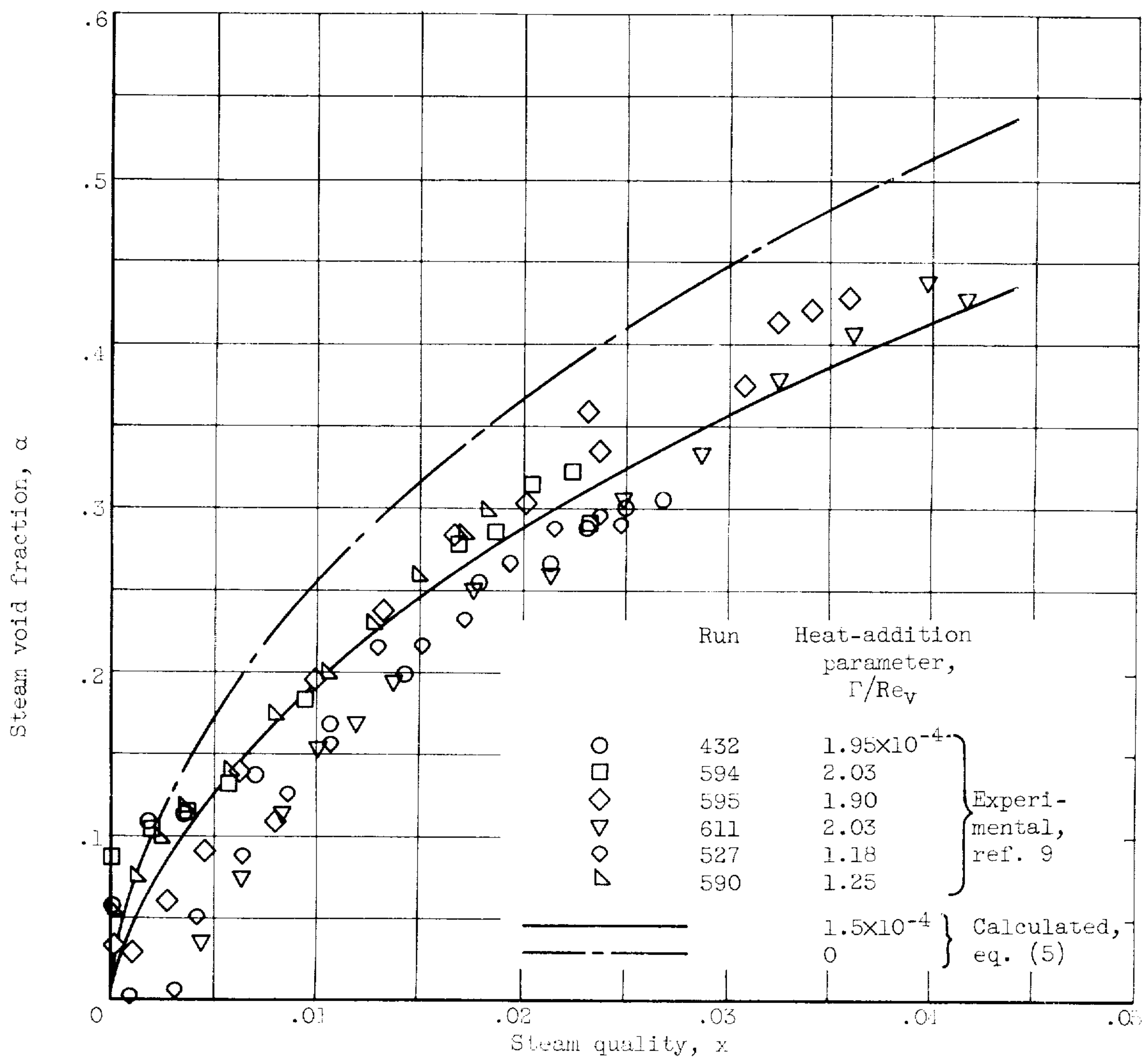
(j) Fluid pressure, 613 pounds per square inch absolute; unrestricted natural circulation; tube diameter, 0.25 inch.

Figure 6. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



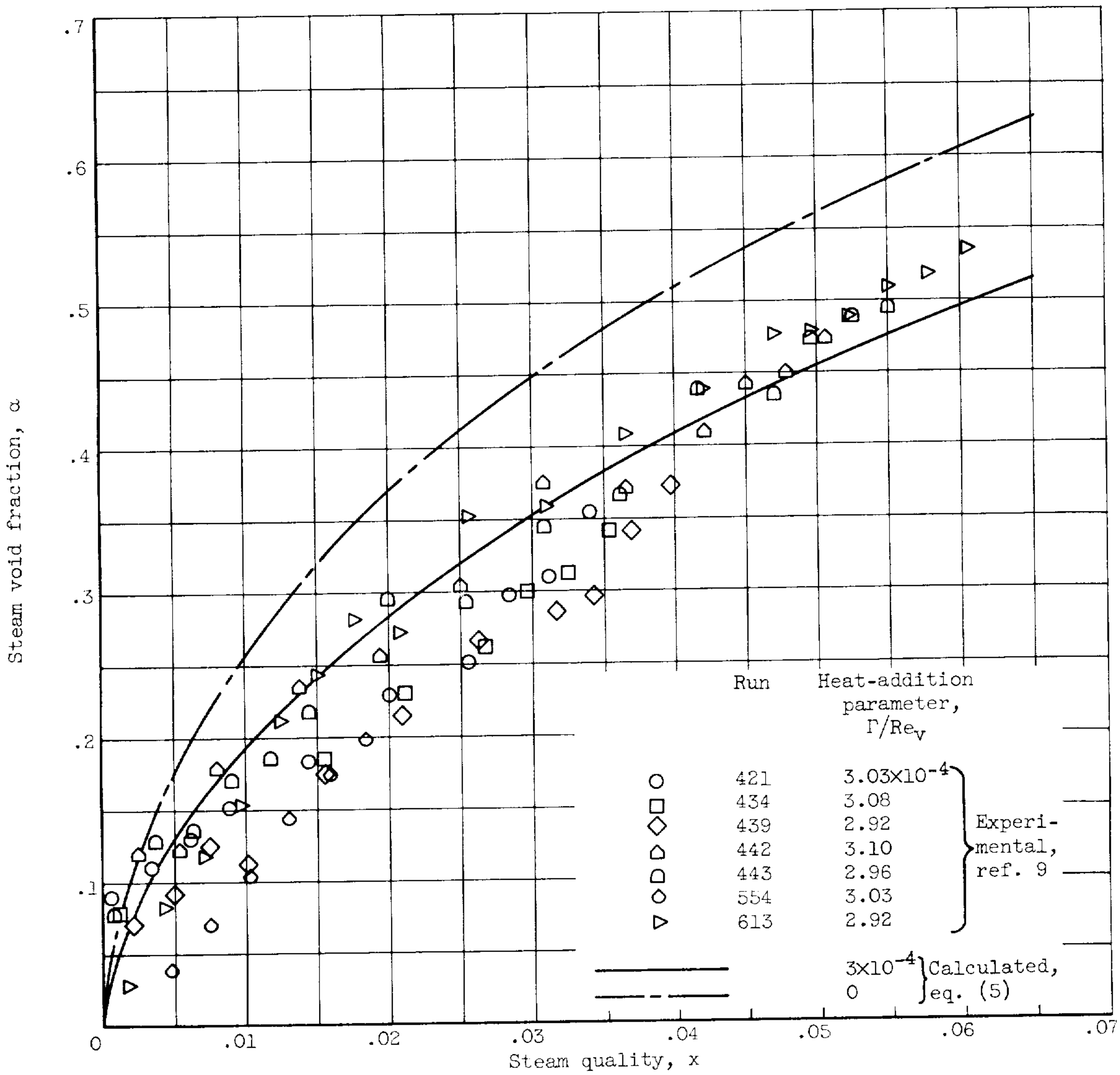
(k) Fluid pressure, 613 pounds per square inch absolute; tube diameter, 0.25 inch.

Figure 6. - Concluded. Comparison of void-fraction values calculated from equation (5) with natural-circulation and forced-flow experimental data for various heat additions, mass velocities, and fluid pressures.



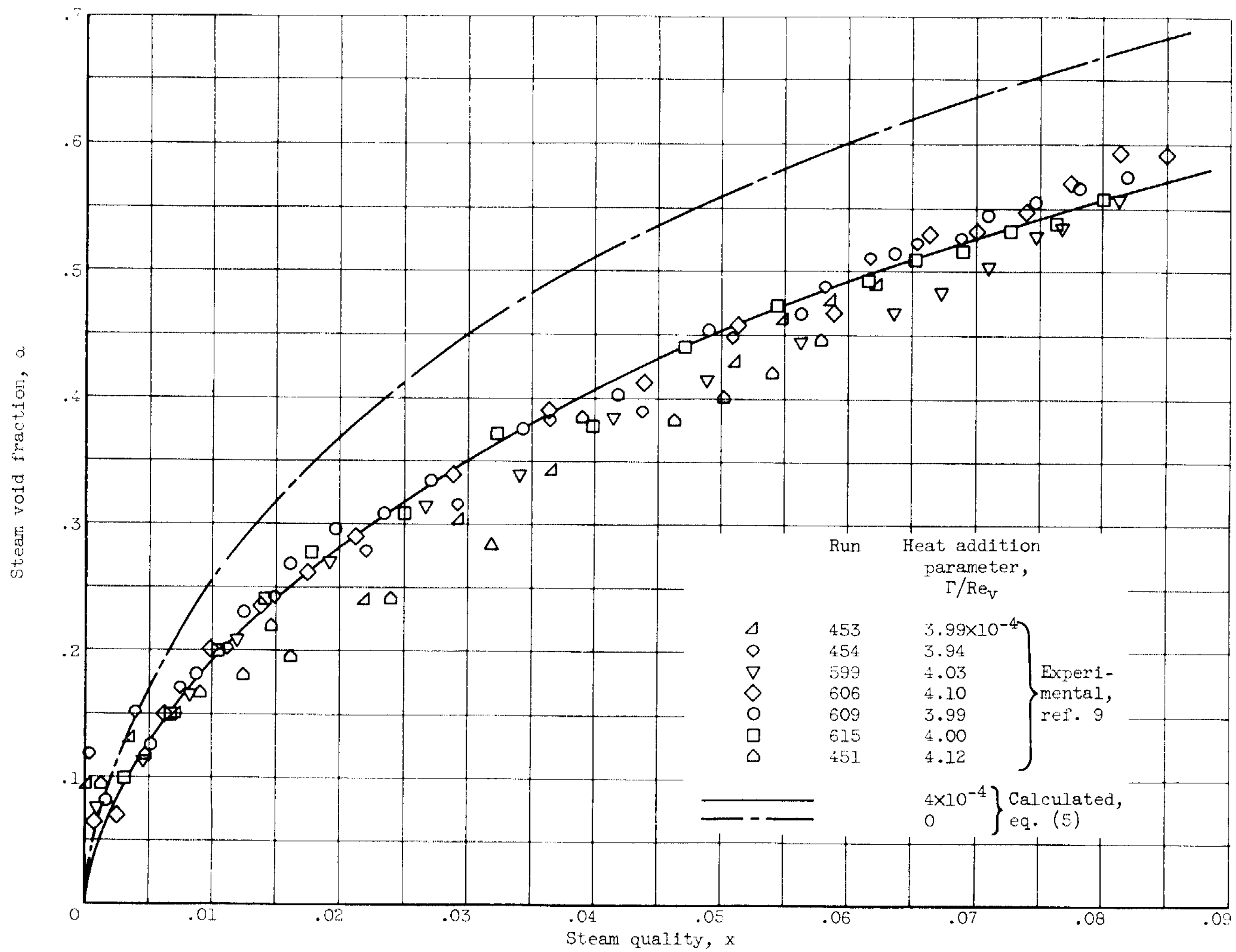
(a) Heat-addition parameter, approximately 1.0 to 2.0×10^{-4}.

Figure 7. - Comparison of void-fraction values calculated from equation (5) with natural circulation experimental data at 613 pounds per square inch absolute for various heat additions and verticle flow. Multiple rectangular channels.



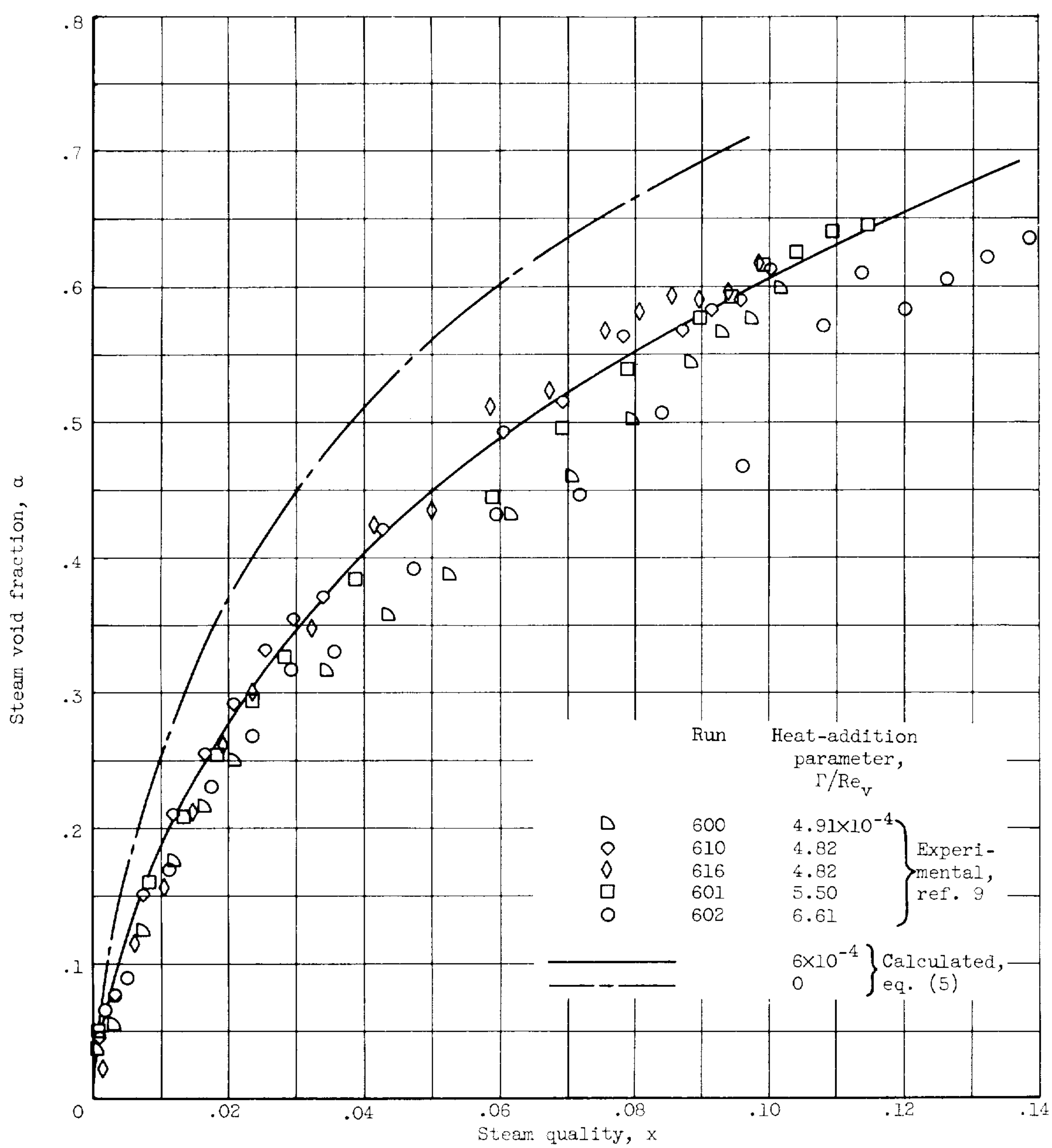
(b) Heat-addition parameter, approximately 3.0×10^{-4}.

Figure 7. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation experimental data at 613 pounds per square inch absolute for various heat additions and vertical flow. Mutiple rectangular channels.



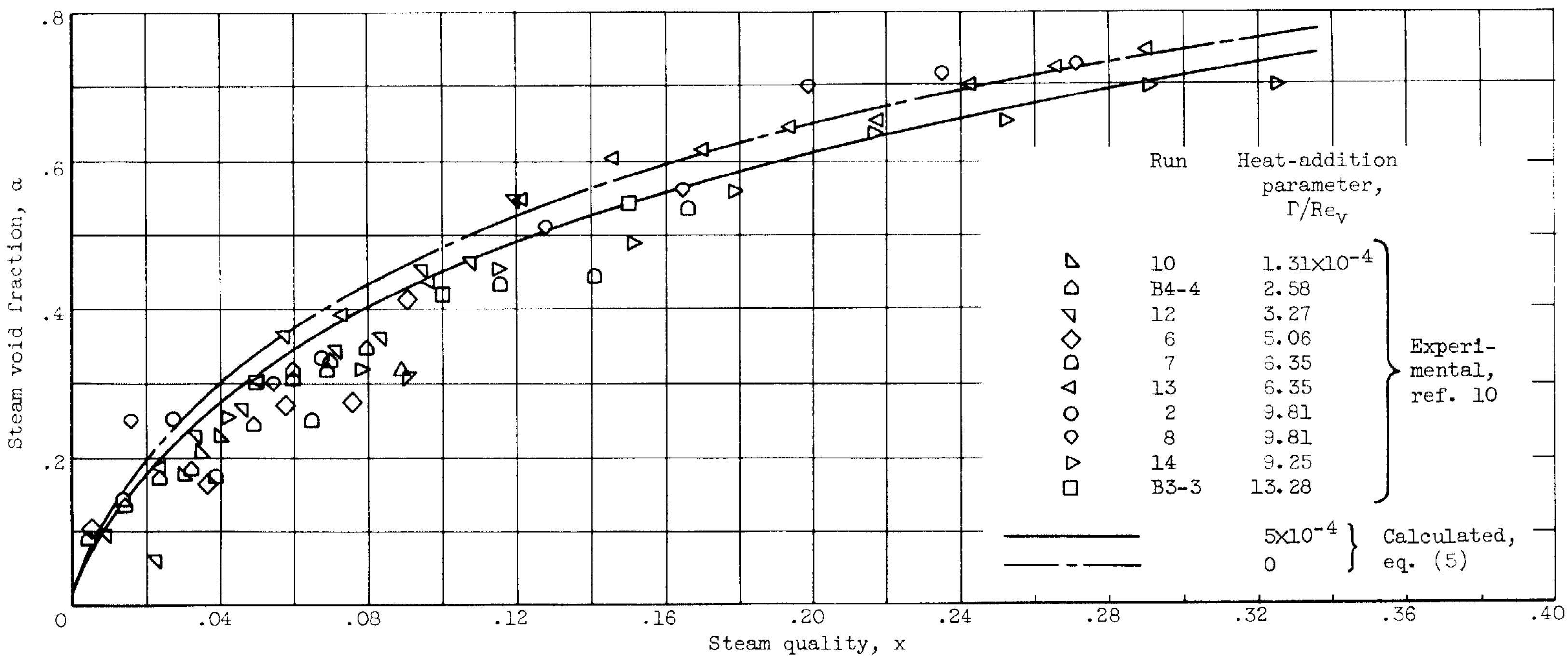
(c) Heat-addition parameter, approximately 4.0X10^{-4}.

Figure 7. - Continued. Comparison of void-fraction values calculated from equation (5) with natural-circulation experimental data at 613 pounds per square inch absolute for various heat additions and vertical flow. Multiple rectangular channels.



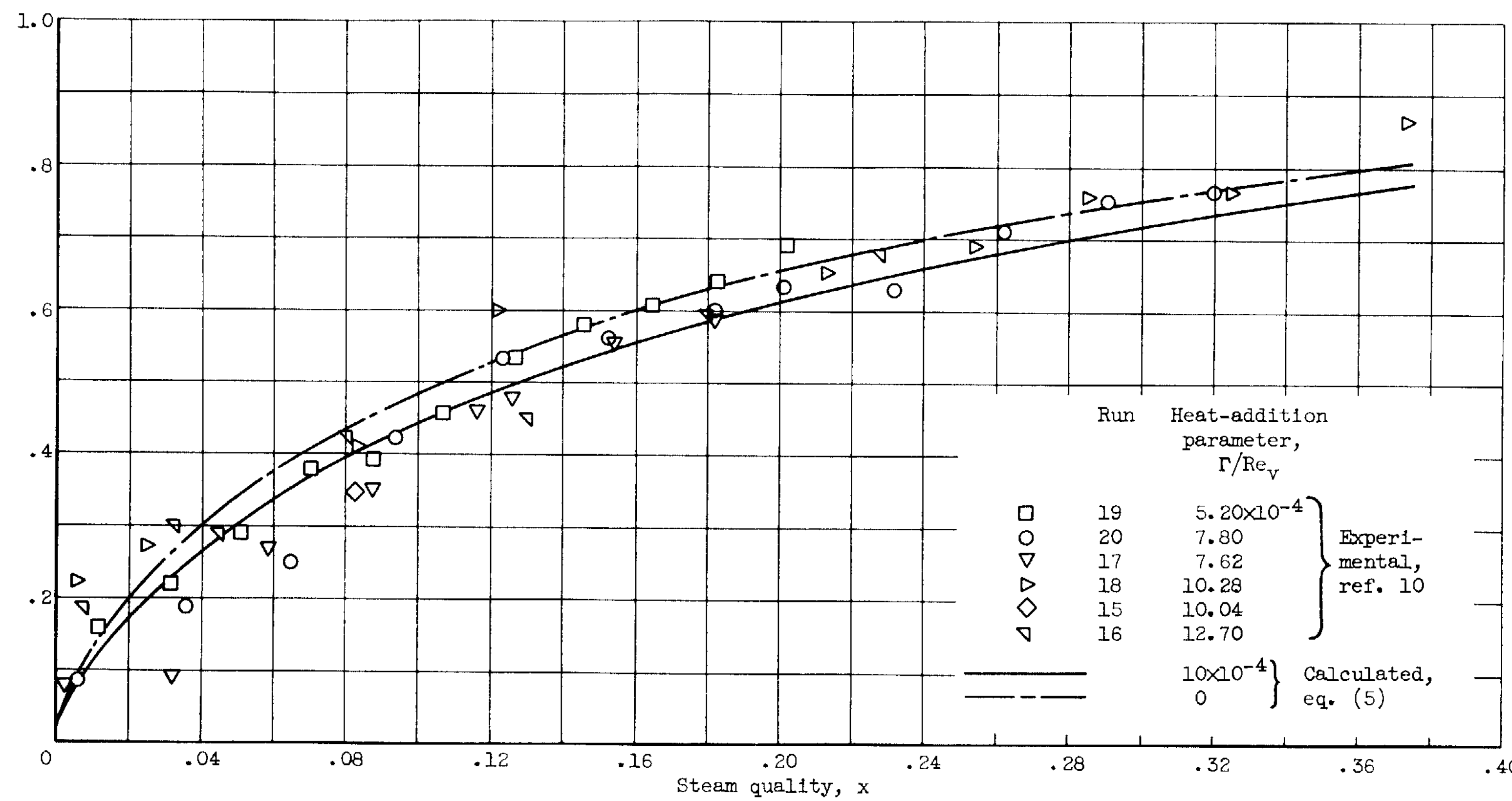
(d) Heat-addition parameter, approximately 4.8 to 6.6×10^{-4}.

Figure 7. - Concluded. Comparison of void-fraction values calculated from equation (5) with natural-circulation experimental data at 613 pounds per square inch absolute for various heat additions and vertical flow. Multiple rectangular channels.



(a) Mass velocity, 0.7×10^{6} pound mass per hour per square foot.

Figure 8. - Comparison of void-fraction values calculated from equation (5) with experimental data at 2000 pounds per square inch absolute for various heat additions and mass velocities.



(b) Mass velocity, 0.9×10^6 pound mass per hour per square foot.

Figure 8. - Concluded. Comparison of calculated void-fraction values calculated from equation (5) with experimental data at 2000 pounds per square inch absolute for various heat additions and mass velocities.